A Review of Intelligent Controller, Sensing and Communication, and Human Factors Aspects for Information-Aware Connected Autonomous Vehicles

Ankur Sarker, *Student Member, IEEE*, Haiying Shen, *Senior Member, IEEE*, Mizanur Rahman, *Student Member, IEEE*, Mashrur Chowdhury, *Senior Member, IEEE*, Kakan Dey, *Member, IEEE*, Fangjian Li, *Student Member, IEEE*, Yue Wang, *Senior Member, IEEE*, Husnu S. Narman

***Abstract*—Autonomous vehicles (AVs) are equipped with a rich set of sensors, such as radar, light detection and ranging (LIDAR), global positioning system (GPS), odometer, and camera, which are used to detect their surroundings by analyzing sensors data to develop collision free path and route the desired destination. To achieve the user acceptance, reliability and comfort of an AV system, it is necessary to push technological advancements and multi-disciplinary research not only, on sensing technologies and control systems, but also on communication (i.e., vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I)) technologies and human factors. AV systems with V2V and V2I capabilities can build Connected Autonomous Vehicle (CAV) systems. However, it is very critical to design a CAV system, which can sense and communicate with its surroundings and ensure system reliability, safety, and users' comfort. In this paper, we conducted an in-depth review on three key aspects of CAV systems: communication-aware controller design, sensing and communication technologies, and human factors. AV controller is the heart of any CAV systems. Communication technology can improve the CAV controller, that can support safety, stability, and comfortable operation of the AVs. Traditional AVs are equipped with different sensing (i.e., radar, LIDAR, camera, and GPS) and communication technologies (V2V and V2I) to provide reliable information to the controller. As human will be the user of CAVs, diverse human factor issues, such as user acceptance and trust, must be considered to design an AV for mass adaptation. Finally, future research challenges for designing the CAV systems have been identified with the goal of motivating the design of more advanced technologies that integrate the three areas for CAVs.**

***Index Terms*—Connected Autonomous Vehicles, Information-Aware Controller, Autonomous Driving, Sensing and Communication Technologies, Human Factors**

I. Introduction

Autonomous vehicle (AV) field testing began in 1977 in the United States when the Partners for Advanced Transit and Highways (PATH) program at the University of California Berkley developed a platooning application of six AVs in specially guided highway sections [1]. Since, the most significant AV development was prompted by the Defense Advanced Research Projects Agency (DARPA) Urban Challenge 2007, which accelerated private sector AV research and development. Since then, major automobile companies including internet giant Google have developed the prototypes of fully AVs that need no special highway infrastructure to operate in mixed traffic scenarios [2], [3]. To facilitate the development of AV technologies, several US states issue special permits to AV technology manufactures conducting pilot testing, most notably in California, in which public input is now being sought for the draft of automated vehicle laws, paving the way for AV licensing [4]. This interest in AV technology from both the automotive industry and the public will advance the development of fully autonomous vehicle development in the next decade.

The Society of Automotive Engineers (SAE) has a classification scheme for autonomous vehicles with six levels: no-automation (level 0) to full (level 5) [5]. Full vehicle automation enables maximum benefit in terms of traffic safety, efficiency and environmental impacts. According to a recent study [6], AVs require more key insights from different complex, inter-dependent factors of transportation systems (i.e., safety data management and utilization, understanding human driving behaviors, and heterogeneous sensors managements). It is reported that more than 75% of US drivers are not comfortable at all to use any kind of AVs [7]. Recent tragic crashes of Tesla autonomous vehicle in China and the US highlight the serious life-and-death consequences associated with malfunctions of autonomous vehicles [8]. The technological advancements and advanced inter-disciplinary ongoing research toward AVs would help users to overcome trust issues of fully AVs [7]. It also requires the overall study of human factors to make the riding experience more comfortable and safer from AV user's perspective [9].

The fully autonomous vehicle can realize the self-driving task merely with the support of the on-board sensors and global positioning system (GPS). However, the fast-growing communication and sensing technologies enable the AVs to utilize more information to improve the system stability and reliability. Vehicle can obtain the information beyond the scope of the on-board sensors from the surrounding vehicles and roadway infrastructures (e.g., traffic signal controllers, roadside unit) to achieve maximum benefit with minimum sensor cost. AV with vehicle-to-vehicle (V2V) and vehicle-

A. Sarker and H. Shen are with the Department of Computer Science, University of Virginia, Charlottesville, VA 22903 USA. Email: {as4mz,hs6ms}@virginia.edu.

M. Chowdhury and M. Rahman are with the Glenn Department of Civil Engineering, Clemson University, Clemson, SC 29634 USA. Email: {mac,mdr}@clemson.edu.

K. Dey is with the Department of Civil & Environmental Engineering, West Virginia University, Morgantown, WV 26506, USA. Email: kakan.dey@mail.wvu.edu.

F. Li and Y. Wang are with the Department of Mechanical Engineering, Clemson University, Clemson, SC, 29634. Email: {yue6,fangjil}@clemson.edu.

Husnu S. Narman is with Marshall University, Huntington, WV 25755 USA. Email: narman@marshall.edu.

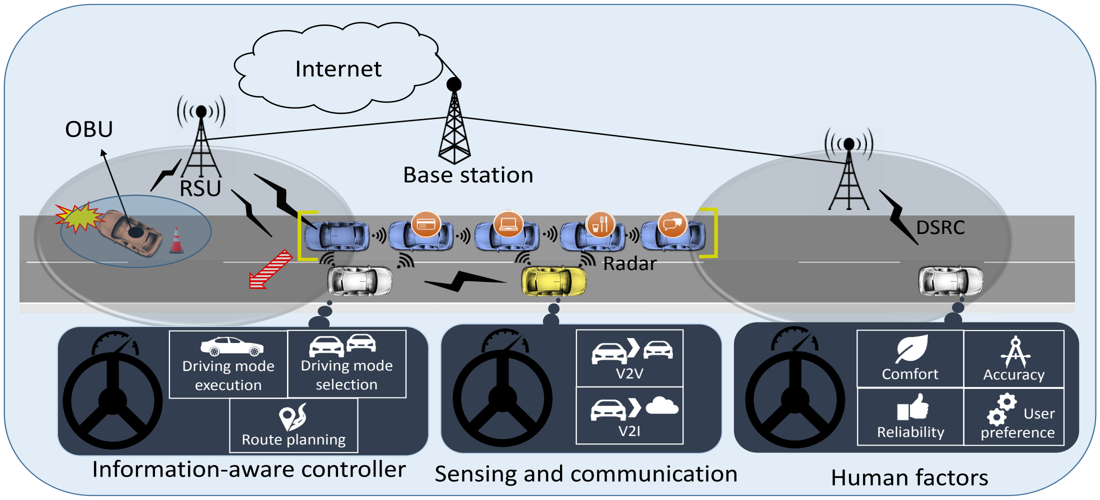


Fig. 1: Information-aware connected autonomous vehicles (CAVs) systems.

to-infrastructure (V2I) communication can be called as *Connected Autonomous Vehicle* (CAV). Fig. 1 shows an example, where a platoon of CAVs are moving closely driving in the right lane and other three CAVs driving in the left lane. The platoon of the CAVs is managed by first CAV and the platoon is going to change the lane to avoid a roadway traffic incident notified by the road side unit (RSU). Here, CAVs can sense other vehicles using Radar and CAVs can communicate with other vehicles through RSU using Dedicated Short Range Communication (DSRC). Eventually, CAVs are able to receive traffic information (e.g., position, velocity, acceleration) of its surroundings to feed into the information-aware controller. In addition, CAVs consider human factors to increase users' comfort and safety. The three main design factors of the CAV system can be summarized as follows:

Communication-aware controller design. As the heart of the CAV systems, the communication-aware controller design is critical for safety, efficiency as well as the traffic throughput. Since the V2V and V2I technology enable the controller to acquire the information beyond what on-board sensors can detect, it can be expected that the CAV will become safer and more efficient by utilizing the additional information from surrounding infrastructures and vehicles. Therefore, many control schemes have been developed to explore the benefit of the communication information, such as the model-based predictive control and learning-based control. The enhancement brought by the communication technology can be found in every layer of the control structure as shown in Figure 1. In addition, the V2I communication makes it possible to realized a centralized management system, which has shown a great potential to further optimize the overall traffic behavior.

Vehicular sensor and communication technologies. Sensor and communication technologies (e.g., radar, L-idar, camera, DSRC, and so on) enable the fully autonomous vehicles to sense its surrounding environments and communicate with other vehicles or infrastructure such that fully autonomous vehicles would able to receive or send messages in time and act properly and quickly. As Fig. 1 shows, the two major components of sensing and communication technologies are inter-vehicles and vehicle communicating with others. The deployment of vehicular sensing and communication technologies toward CAVs bring significant safety, mobility, and environmental benefits over traditional vehicles [10].

Human factors. Mass adoption of connected autonomous vehicle systems depends on the user comfort, trust (i.e., accuracy and reliability) and preferences (as shown in Figure 1) [11], [12]. CAV must provide a reasonable level of user acceptance. A reasonable level of AV user acceptance depends on the individual's preferences based on their age, gender, cultural and societal characteristics [13], [14]. CAV must ensure acceptable vehicle dynamics (i.e., maximum speed, maximum acceleration/deceleration), headway (i.e., bumper-to-bumper distance between vehicles), gap for changing lane and string stability (i.e., sharp fluctuations of position, speed, and acceleration/deceleration) in different traffic conditions (e.g., congested, free flow) depending on the individual preferences. It is required to implement human driver model (i.e., driver car-following behavior and lane changing behavior model) for designing a path planning controller to include user preferences as per their expectations [15].

In this paper, we reviewed existing literature related to CAV systems in terms of the design of communication-aware controller design, sensing and communication technologies, and human factors. There are several review studies [16], [17] on different aspects (e.g., communication, controller, and human factors) of future generation intelligent transportation systems (ITS). As an example, our previous survey paper [18] gives a comprehensive review of the design of cooperative ACC (CACC) systems under communication effects and consideration of human factors. However, this paper focuses on identifying the effects of controller design criterion, sensing and communication technologies, and human factors for a fully AV design.

The structure of the paper is as follows: Section II presents a discussion on the communication-aware controller designs for CAV systems. Then, Section III presents an overview of sensing and communication vehicular technologies with existing research works on the vehicular networks for CAV systems. Then, Section IV discusses human factors for designing a CAV and presents related works on driver behavior modeling for CAV systems. Section V presents research challenges and research directions for fully autonomous connected vehicular systems. Finally, Section VI concludes this paper.

II. Communication-Aware Controller Design

According to the SAE classification [19], the functional structure for an AV with Level 5 automation is composed of 5 layers: perception, localization, route planning, driving mode selection, and driving mode execution [20]. The different layers are shown in Fig. 2. Firstly, the main task of perception layer is to perceive the environment based on the information collected by different sensors. Secondly, localization is required to locate the position of the subject AV on a given map. Thirdly, the route planning is responsible for a general route to the destination. Fourthly, driving mode selection is built to determine automatically which driving mode should be chosen under current roadway traffic condition. For the fully autonomous vehicle, the driving modes are switched automatically based on the driving situation. Example modes include the car-following mode and lane-changing mode. Finally, the chosen driving mode is executed under the cooperation among sensing system, control algorithm, and actuators. It has been demonstrated that information from on-board sensors and GPS is enough for the realization of an AV [21]. The emergence of the vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication technology can provide the vehicle with additional information beyond what the on-board sensors can detect, such as the velocity of the leading vehicle. This additional information can further improve the efficiency and safety of autonomous driving [22]. Among the five layers of the controller, perception and localization are more relevant to the traffic information collection, such as vehicles position, velocity and acceleration, which are used as the input for the AV controller, which is beyond the scope of this review paper. In the following paragraphs, we focus on the intelligent controller design in terms of the other three different layers and discuss how the communication can benefit the controller design.

A. Route Planning Layer

The route planning layer develops an optimal route to the destination based on various criteria, such as the shortest distance, shortest traveling time, and avoidance of tollways. For an AV that fully relies on the on-board sensors, as shown in Fig. 3a, the optimization of the route depends on the information in the given map, such as route distance and tollways information [23]. In this case, the shortest traveling time option is hard to achieve since there is no information about the real-time traffic conditions, such as the roadway traffic congestion and incident. When the sensor-based AV meets such scenarios, alternate route planning will not be efficient in terms of travel time and energy consumption [24], [25]. To solve this problem, V2I communication technology can be adopted to provide the CAV controller with real-time traffic conditions [26], where distributed control scheme plans the optimal route individually for each CAV. Hence, the chosen route can be optimized initially with respect to the travel time and has a prompt response to traffic dynamics which is shown in Fig. 3b. In addition, an optimal route planning from a centralized controller can also be realized via the adoption of V2I communication as shown in Fig. 3c, where the optimal routes of different CAVs are calculated coordinately by considering their impacts on the overall traffic condition [27]–[29]. The details about how the communication can benefit the route planning layer are discussed in the following paragraph.

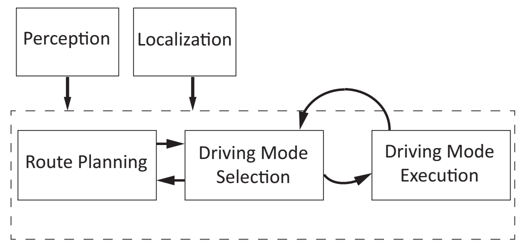


Fig. 2: Controller block diagram.

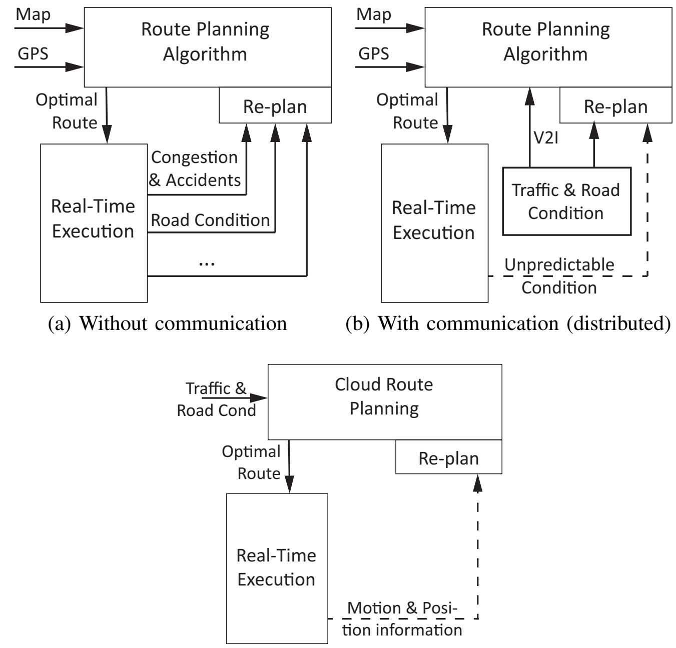
Communication-Aware Route Planning: In [26], motion states information of different vehicles is gathered in the cloud via V2I communication. Then, the traffic simulation software AIMSUN [30] is utilized by the individual CAV to predict its corresponding future traveling time for each roadway segment. Finally, the fastest route is derived by minimizing the overall traveling time via the modified Dijkstra's algorithm where the cost of each segment is time-varying predicted traveling time. However, this distributed optimization for each individual CAV might switch the congestion from one spot to another. To deal with this congestion switch issue, the Entropy Balanced k Shortest Paths (EBkSP) strategy is proposed in [27], where the route selections of all CAVs on the road are managed by a centralized controller via V2I communication. The impact of each individual vehicle route selection on the roadway traffic congestion is calculated considering other vehicles information on the route via the extensively used Greenshield's model [31] at each time interval. Then, multiple optimal routes are generated simultaneously based on the minimization of the road congestion. Moreover, the optimal routes are assigned upon the priority ranking to CAVs based on urgency of the driving task. In [28], the real-time traffic congestion information is considered in building the cost of the route segment in combination of the route length. As a result, the optimal route considers both the travel time and distance when minimizing the overall cost along the chosen route. In addition, to realize an optimal route selection, the dynamics of the intersections are incorporated to predict the traffic dynamics under different route selections. Moreover, the perfect communication condition is not realistic, which inspires more works to study the communication imperfection in the control algorithms. By considering the limited V2I communication coverage area issue, a novel route re-planning algorithm is provided in [29]. A centralized route management controller is adopted to deal with the route planning issue for the connected vehicle in traffic congestion area. The coverage of the road side unit (RSU) is considered, which means the centralized controller only takes charge of the route planning within the RSU covered area without changing the ending route point on the edge. For the uncovered area, the AV follows the original plan initiated from that ending route point.

B. Driving Mode Selection Layer

Driving mode selection layer determines which driving mode should be chosen based on the knowledge of the roadway traffic situation, such as the position and velocity information of neighbor vehicles. There are numerous driving modes in dealing with different situations, such as car-following, lane-changing (merging, leaving), obstacle avoidance, and parking. For the AV with the on-board sensors only, it can still realize the driving mode selection with the guarantee of safety [32]. However, it cannot identify the neighbor vehicles intention or the future motion states directly due to lack of communication among vehicles, which is essential for the selection of the driving mode. Although learning-based algorithms can be used to predict such information [33], the driving efficiency might be sacrificed when dealing with the uncertainty of the neighbor vehicles' driving trajectories. Generally, additional information via communication can contribute to a reasonable driving mode selection, which will be explained in the next paragraph. However, some of the driving modes are determined by the chosen route, such as the intersection and merging/diverging sections. In the following paragraph, we mainly summarize the scenarios where the AV has the freedom to choose the driving mode, such as the obstacle avoidance and lane-changing decision.

For the AV without communication capability, the distance and speed information of the host vehicle and the neighbor vehicles is mainly used to design the control algorithm. In [34], three inter-vehicle status regions (i.e., I, II, and III) are classified based on the relative velocity and headway between the host vehicle and front vehicle/obstacle. If the rear-end collision can be avoided by a mild deceleration (region I), the host vehicle will continue following its front vehicle by applying the brake. If the desired deceleration is too large, the lane-changing (region II) or both deceleration and lane-changing (region III) should be applied. A priority based algorithm is proposed in [35], where a complex traffic situation can create potential conflicts among different driving modes, i.e. multiple modes can be activated simultaneously by the low-level logic. To deal with this issue, the priorities have been assigned to different driving modes to prevent the potential mode conflicts, for example, safety-relevant obstacle avoidance has the highest priority. For the lane-changing mode, prevention of collision should be the constraint.

Communication-Aware Driving Mode Selection: First of all, the communication technologies can provide accurate and prompt motion states without the constraints brought by the on-board sensors such as the relative position. Therefore, the algorithm proposed in [36] utilizes the V2V communication technology to derive relative speed and distance with respect to the front vehicle. As can be expected, this algorithm has a fast and accurate decision in whether to adjust the speed or conduct a lane-changing maneuver to deal with the slow front car/obstacle. Besides the advantage of the higher quality



(a) Without communication (b) With communication (distributed)

(c) With communication (centralized)

Fig. 3: Route planning comparison.

information, V2V communication enables the negotiation between CAVs to improve the decision-making process. In [37], the pre-calculated trajectory of the host AV is shared with its neighbor vehicles. Correspondingly, the negotiation mechanism is designed to conclude the final trajectory. This negotiation before the action will surely enhance the effectiveness of the AV's decision-making. For example, when the slower vehicle is detected ahead, the AV only with on-board sensors cannot determine whether the slow-moving front vehicle will change to the right lane in the next few seconds. Here, with the negotiation and information sharing between vehicles, this dilemma can be eliminated.

In addition, V2I communication enables a centralized controller to collect motion states information of all CAVs. Hence, the centralized traffic management controller can realize a global optimization. Under this scenario, the driving mode selection of CAV is assumed to obey the regulation from the traffic management controller. Based on the assumption that the centralized controller knows all the traffic information via V2I communication, a centralized traffic flow controller is proposed in [38] to optimize the traffic flow rate. In this centralized controller, a macroscopic traffic flow model is adopted where traffic segment speed, lateral (lane-changing) flow, and the freeway ramp entering rate are the control inputs. All these three control inputs are calculated optimally by minimizing the quadratic traffic congestion cost function. Moreover, the flow rate control signal is then desegregated into the individual vehicle controller command to the CAVs. In [39], the model predictive control approach is used to deal with a similar traffic flow optimization task, but considering the existence of manually driving vehicles, where the manual driving flow model is calibrated by traffic pattern observation. In addition, the control input of the traffic dynamics becomes the manipulation of CAVs instead of all the vehicles in the mixed traffic flow.

C. Driving Mode Execution Layer

In this section, we will introduce how communication can help to execute appropriate driving modes.

1) Car-following Mode: For the AV without communication function, the autonomous car-following mode is called an adaptive cruise control (ACC) system, which is used to maintain a reasonable headway between the front vehicle and the following vehicle [40]. There are numerous criteria for the desired headway, such as collision avoidance and human factors that will be covered in Section IV. ACC system mainly collects the headway and velocity information as the input of the controller to determine the desired acceleration. There are two stability requirements [41]: individual stability and string stability. For the individual stability, it requires that AV should track the desired headway successfully. For the string stability, it requires that the fluctuation of the motion state should not propagate upstream. Constant time headway is a widely adopted spacing policy to define the desired headway, which requires the desired headway equal to a constant times host vehicle's velocity plus a minimum space [42]. In general, the typical proportional-integral-derivative (PID) controller [43], [44] or the sliding mode controller [45] can minimize the headway error and guarantee a string stable ACC design even under the effect of the dynamic delay.

When the information from V2V or V2I (V2X) communication is utilized in ACC design, the controller becomes the cooperative adaptive cruise control (CACC) system. Since the V2V and V2I communication technologies are used, there is freedom for the controller to utilize various information from platoon with less limitation on the information type and relative position that is produced by CACC without V2V and V2I communication support. Currently, several communication topologies have been investigated including the predecessor-following (PF) topology, the bidirectional (BD) topology, the predecessor-following leader (PFL) topology, and the two predecessor-following (TPF) topology [46]. There are lots of controller structures for CACC systems. In [47], the design utilizes feedforward controller with communication information in combination with the conventional ACC feedback controller. It is found that CACC system can realize a shorter time headway than the ACC system with the guarantee of string stability. In addition, this CACC system controller structure has a better performance in minimizing the velocity fluctuation upstream with the help of feedforward communication path [48]. Moreover, V2X communication can enable controller to deal with new challenges via the advanced control algorithms. The reinforcement learning approach is adopted in [49] to enhance the controller performance using high-fidelity nonlinear vehicle dynamics. The simulation shows that this novel CACC controller can guarantee an efficient tracking of the desired inter-vehicle distance. In [50], the model predictive control (MPC) method is used, which takes motion states deviation and its effects on its following vehicle into consideration in building cost function. When the MPC controller is adopted, different objectives can be realized by customizing the computationally feasible cost function. For example, jerk minimization can be considered in the cost function with an objective to enhance the human driver's comfort [51].

2) Lane-Changing Mode: It is critical for the lane-changing controller to make sure that no collision will occur when the AV changes from the current lane to the desired lane. With the guarantee of safety, the lane-changing trajectory is generated, and a vehicle lateral dynamic controller is used to track the trajectory. In this section, the lane-changing collision risk analysis with V2V communication is discussed. To guarantee the safety, Davis et al. proposed that the headway between the host vehicle and the vehicles in the desired lane should be a function of the following vehicle's velocity and the velocity difference from preceding car [52]. In [53], the reference velocity is designed for the AV merging into the automated vehicle platoon. In the end of the merging process, the velocity should equal to the platoon velocity and the headway should also match the desired vehicle-following space. In addition, the minimum space should always be kept during the merging process. While, the maximum level of the acceleration and deceleration of neighbor vehicle is considered when calculating the collision-free trajectories, which comes with the sacrifice of driving efficiency. In addition, the velocity fluctuation is inevitably introduced to decrease the riding comfort if the vehicle suddenly merges into the desired lane without any negotiation.

In [54], a slot-based merging algorithm is proposed with the utilization of V2V communication. When the vehicle intends to merge into the desired lane, the slot-based traffic management system (TMS) will find an empty slot for the vehicle after negotiation with the neighbor vehicles or reject the request in case of slot unavailability. By adopting V2V communication, safety can be guaranteed without using the conservative mathematical constraints which assume the maximum acceleration level will be adopted by neighbor vehicles. Moreover, the vehicles in the desired lane have more time to prepare for lane changing, which can minimize the velocity fluctuation. A proactive traffic merging strategy is developed in [55] to improve the merging efficiency. If there is a vehicle merging into the desired lane or highway, the vehicles in the desired lane will be notified via V2V communication and the pre-computed lane-changing space will be reserved before the vehicle arrives at the merging area. Hence, the vehicle can directly merge into the desired lane smoothly. Ideally, this pre-computed trajectory negotiation can eventually be used to realize a fluctuation-free lane changing action.

3) Intersection Mode: For an AV without communication capability, it will follow the roadway traffic rules, such as the stop sign and traffic signals when driving in the intersection mode [56]. However, the V2X communication technology can offer a more efficient and safer roadway intersection driving mode.

First of all, V2I communication transmits the traffic signal information to CAVs. Hence, the CAVs can utilize this additional information to operate the controller for intersection mode. In [57], the constant acceleration level and duration are calculated to avoid the red traffic light indication. It was shown that this algorithm can significantly improve the overall fuel economy and traffic throughput. Moreover, multiple traffic signals are considered in [58] to calculate the desired velocity range. When the first traffic signal can be passed within a specific velocity range for the CAV, the controller will continue checking the feasibility of passing the next traffic signal. The final velocity range is determined when the CAV will inevitably stop at the next intersection i.e. there is no feasible velocity range to pass all the traffic signals. Secondly, the V2V communication is more helpful at the intersection without the guidance of traffic signal, where efficiency is heavily deteriorated by the rigid traffic stop sign law. In [59], V2V communication is used to broadcast the position and velocity information to other vehicles within the intersection area. To cross the intersection, the AV should yield to the vehicles with higher priority based on the traffic rule. A fuzzy logic controller is designed to control the level of the throttle and brake based on the headway and inter-velocity with respect to the higher-priority vehicles. Moreover, the intersection control agent (ICA) is designed [60] as a centralized controller to manage the intersections crossing CAVs via V2I communication. Every vehicle trajectory is managed to make sure that there is no overlap in the intersection area to prevent collision. If overlap is inevitable, the vehicle with a lower priority in the queue will be stopped. In addition, the corresponding stop recovery algorithm is designed to guide the stopped vehicle in the intersection scenario. In [61], the simulation shows the intersection crossing efficiency and fuel economy are improved comparing with other methods such as the actuated control.

From the review above, it is clear that V2X communication can enhance the performance of AV controller since more information can be used to improve the controller efficiency and the performance in dealing with the uncertainty of the roadway traffic condition. In addition, V2I communication can further contribute to building the centralized controller, where global optimization can benefit the overall traffic condition. In the next section, we will discuss the sensing and communication technologies that can enable the CAV to collect information from traffic.

III. Sensor and Communication Technologies

It is expected that CAV will provide high standards for safer transportation in different modes of road transposition systems by intelligently managing and controlling vehicles and road infrastructure. One of the crucial components which enables this type of managing and controlling mechanism is cooperatively sensing and networking between different components to optimize both common and individual goals. Using 2004-2008 crash data, a breakdown analysis by the US Department of Transportation (USDOT) states that communication and sensing technologies inside vehicles could help avoid up to 79% of all traffic accidents [62]. Different safety applications (i.e., forward collision warning, emergency electronic brake light, left turn assist, and blind spot warning and lane change warning) can be offered by sensor and communication technologies for semi AVs or fully AVs [62]. For example, left turn assist warns the driver of a vehicle, not to turn left in front of another vehicle traveling in the opposite direction. There are also some other scenarios where sensor and communication technologies of vehicles can improve the traffic flow and increase the throughput of the existing road network. As an example, vehicles can be warned by pedestrians crossing a road section. Additionally, sensor and communication technologies can be deployed to harmonize each vehicle's velocity on the road, control traffic signals, and their times to improve the riding experiences, etc.

In this section, we first introduce different sensing technologies and research trends of these sensing technologies to increase the safety and traffic efficiency of CAV systems (Section III-A). Then, we present the basic V2V and V2I communication architecture and existing research directions on communication technologies (Section III-B). Finally, we discuss some promising technologies and their research trends for future generation CAV systems (Section III-C).

A. Sensor Technologies

Several advanced collision avoidance technologies already available employ different on-board sensor technologies (e.g., RADAR, cameras, and LIDAR) to monitor vehicles surroundings. These existing "vehicle-resident" technologies are installed inside a vehicle but do not communicate with other vehicles [63]. RADAR, cameras, and LIDAR installed inside the vehicle are able to collect information directly by sensing the surroundings. As a result, these collision avoidance technologies are able to use surroundings' information to warn the driver about possible hazards so that the driver can take necessary actions to avoid or mitigate the hazards.

1) Radar: Radar emits radio waves to detect the presence of objects by using the time interval between sending radio waves and receiving reflected radio waves. It can also detect the direction of the objects' movements. There are mainly two types of radar systems: short-range radar (SRR) and long range radar (LRR). SRR is only able to detect objects within 20 meters, uses only a single antenna, and cannot detect angles. It can be used in parking assistance and blind spot warning scenarios. 79 GHz frequency range is designated for SRR equipment on a noninterference and non-protected basis with a maximum mean power density of -3 dBm/MHz associated with a peak limit of 55 dBm [64]. However, LRR can detect any objects within 150 meters with an angular regulation of two degrees. As a result, LRR is able to detect the velocity of objects heading away or toward it. It can be used in forward collision warning and intersection managements. Also, the 77 GHz frequency range of LRR equipment allows the combination of -40dBm/MHz transmit power, more than 250 MHz bandwidth, long range operation, and high distance separability at the same time [64]. For example, radar-based pulse doppler framework is able to detect and then track objects in front of vehicles [65] where the radar system is installed on the lower part of the vehicle. It can detect objects and their relative speeds within 150 meters based on consecutive echoes of sent radar signals.

This kind of system also detects different vehicles in multiple lanes in real time simultaneously, based on a discrete time signal processing technique, and can detect vehicles in adverse weather conditions (fog, rain, etc.) [66].

2) Camera: Since cameras are able to detect color and object boundaries, cameras are used to detect the road lanes and read traffic signs. However, cameras can also easily measure rates of change between objects ahead, like whether a driver is gaining on a slower moving vehicle, pedestrians, or bicycles. Cameras can deliver spatial and color information that other sensors cannot (Schwarz et. al, 2013). Surrounding object detection may be carried out by a different combination of cameras: such as a single camera [67], [68] and multiple cameras [69], [70]. The placement of cameras may be different based upon their purpose. For example, to detect blind spots, cameras would be mounted nearby the side mirrors and to serve as parking assistance, cameras would be mounted on the back of vehicles. The types of cameras used in vehicles are based on their uses: stereo cameras would be used to obtain wider view [71] while infrared cameras would be used to get good view at night or during bad weather [72], [73]. There are primarily three different approaches to detect the moving objects using camera installed in vehicles: background subtraction methods, the feature based method, and frame inferencing or motion based methods. A background subtraction method may use a filtering method based on a histogram which collects information from sequences of frames of scatter background [74] or each pixel in the image view to categorize as either noise or a forefront entity's background [75]. In feature based methods, the nearby objects are discriminated from the background by using their features [76] and a set of labeled training data are used for feature extraction from the objects [76], [77]. The Haar wavelets technique and support vector machine can be used in these approaches. Similar to background subtraction methods, in frame inferencing or motion based approach, subsequent frames are compared to extract the background and detect nearby approaching vehicles [74], [78], [79].

3) Light Detection and Ranging: Light detection and ranging (LIDAR) functions similarly to radar systems, as it emits laser signals and uses echoed laser signals to calculate the distance of objects around the vehicle. We can easily estimate the distances the photos have covered round trip using the speed of light. LIDAR can measure accurate angles in both horizontal and vertical dimensions and generate three-dimensional data with higher accuracy (within few centimeters error rate) and the generated three-dimensional data are then integrated with two-dimensional GPS data to allow vehicles to navigate their surroundings. In addition, LIDAR is used for aerial surveying and producing high-resolution maps, which are mandatory for AVs to get an overview of their environments. The perception range of LIDAR varies from 10 meters to 200 meters. As an extended version of a laser range finder, a laser scanner estimates the distance to an object based on the time-of-flight principle. A laser scanner is an extended version of a laser range finder, which adopts the time-of-flight principle to calculate the distance to an object. As an example, a two-dimensional LIDAR sensor mounted on a vehicle is used to facilitate parallel parking in the opposite direction where the ranging measurements are processed to estimate the location of the curb and the presence of objects in the road [80]. Then, Occlusion and location reasoning are used to detect vehicles and their surrounding environments.

4) Acoustic Sensors: Mostly used in backing, parking assist, lane keeping, and cruise control features, ultrasonic sensors send out high frequency sound waves that measure echoes to determine the distance of an object. As an example, acoustic sensors collect surrounding environment information by receiving the signals without emitting them [81], [82]. In [82], an acoustic-based sensing method is proposed to extract a robust spatial feature from noisy acoustical observations and then, the spatial features are filtered out using sequential state estimation. The proposed system processes real world acoustic data easily by the vehicle-mounted microphones outside the cruising vehicle. The spatio-temporal gradient method is used to extract the features. Then, the spatial feature is filtered out using sequential state estimation. In another work [81], an acoustic sensing hardware prototype is used to estimate congestion on the road using considering acoustic noises of the surroundings vehicles. It basically samples and processes acoustic noise to calculate vehicle speed distribution and acoustic noise, with speeds estimated from acoustic noise using differential Doppler shift.

Usually, vehicle resident sensors would exhibit reduced reliability in certain weather conditions, such as snow, fog, and heavy rain. In addition, camera systems would exhibit reduced performance because of shadows and transitions of light. Majority of existing sensing technologies are susceptible to show poor performance foreign objects, such as snow or dirt. Communication technologies are able to provide safety of CAV systems, increase traffic efficiencies (i.e., flow control), and eventually, complement the sensing technologies of CAV systems.

B. Communication Technologies

There are different components of a fully-integrated vehicular communication system, such as a general purpose processor and associated memory, a radio transmitter and transceiver, antennas, interfaces to the vehicle's sensors, and a GPS receiver. It generates the "Basic Safety Message" (BSM) based on the information gathered from on-board sensors in the vehicle. An integrated system can both send and receive BSMs, and it can process the information of received messages to provide advisories and/or warnings to the driver of the vehicle.

To provide fully-integrated vehicular networking, Federal Communications Commission (FCC) has assigned 75 MHz bandwidth over the 5.85–5.925 GHz for DSRC-based communication [83]. In DSRC, there are seven channels (172, 174, 176, 178, 180, 182, and 184) with 10MHz bandwidth. Channels 174 and 176 can form channel 175 with 20MHz bandwidth (similarly, channel 181 can be formed by 180 and 182 channels). One of seven channels (channel 178) is called control channel which transmits urgent and management related data, and all other channels are called service channels

TABLE I: DSRC-based communication requirements.

Metric	**Transmmission range**	**Elevation angle**	**Transmission power**	**Packet error rate**
Values	300m	+10 $\sim$ -6	15 dBm	<10%
Metric	**Data rate**	**Sensitivity**	**Bandwidth**	
Value	>6 Mbps	-92 dBm	10 MGHz	

(SCH)[1] [85]. Table I shows the requirements of DSCR system defined by NHTSA. However, the other communication types such as Wi-Fi are not directly suitable for the vehicular environment because of high mobility, channel congestion, and delay sensitive messages [86]. Therefore, physical and medium access control layers (IEEE 802.11p) [87] with additional Open Systems Interconnection layers (IEEE 1609.1, 1609.2, 1609.3, 1609.4, and 1609.11)[2] [88] have been designed to address the communication challenges in the vehicular environment. IEEE 802.11p and IEEE 1609 protocol suites form Wireless Access in Vehicular Environment (WAVE) protocol suite, which determines the architecture and a set of services to enable secure and safe V2V and V2I communications [88]. In the following subsections, we present the architectural overview of the vehicular networks. Then, we discuss existing research works considering V2V and V2I communications.

1) Vehicular Network Architecture: In a vehicular network, there might be several vehicle nodes and RSUs which can communicate with each other (as Fig. 1 shows). The vehicles are capable of communicating with another vehicle in a short range while they are moving. Here, RSUs are equipped to extend the V2V communication range and provide some other application services (i.e., speed advisory, traffic light managements). As we discussed earlier, the goal of the vehicular communications is to ensure safety and efficient traffic flow. The entire architecture is designed to deliver several kinds of information to drivers, passengers, pedestrians, and vehicles. Currently, any vehicle comes with a rich set of communication units [89] such that a vehicle can communicate with other vehicles. For different applications, there would be different application units to store or process the data from communication units and notify On-Board Unit (OBU) accordingly. Vehicles can communicate with other moving vehicles which are out of the communication range by using RSUs as relay nodes. Furthermore, RSUs can also be used to connect to the Internet or other gateways (Fig. 1). Thus, any moving vehicle can access the Internet via RSUs.

The followings are the main component of vehicular network:

a) *Onboard Unit.*
An OBU is basically an IEEE 802.11p enabled communication device which includes a small processor, a memory unit, and a user interface. To communicate with other vehicles or RSUs, an OBU includes an interface which is based on IEEE 802.11x wireless technology. Here, the prior handshaking scheme is excluded from the communication procedures to reduce the communication delay. An OBU may perform several functions (e.g., wireless radio access, ad-hoc routing, geographical routing, reliable message transmission, etc). Inside an OBU, the applications can be mainly divided into two groups: safety-related application and non-safety related application. To support the different applications, there is an application unit which is mounted into OBU; the unit can be a dedicated device for emergency applications or a general purpose internet accessible device. It might be possible that the application unit comes as a part of OBU. Basically, the application unit works as subordinate of OBU based on application criteria.

b) *Road Side Unit.* RSU is based on a DSRC device and the communication range of RSU varies from 500m to 1000m [90]. Since RSUs are static, these would be installed at busy intersections or parking spots where a larger number of vehicles are present and vehicles can have the opportunity to access RSUs. As a backbone of RSU, there should be some base stations or gateways so that RSUs can be connected to the Internet. As a result, RSU can work as a relay node and provide internet connectivity to vehicles. According to [91], the main purposes of RSU include:

Extending the communication range of V2V network: The RSUs can carry and forward messages from one vehicle to another vehicle. Also, RSUs can relay messages to other RSUs and increase the coverage area of the vehicular network.

Running traffic management applications: The RSUs may provide special messages to moving vehicles inside its coverage area about traffic congestion, traffic accident, hospital zone, etc.

Providing internet connectivity: Vehicles may connect with RSU to access the Internet. In this way, RSU may act as a source of information.

In addition, RSUs may run some specific applications, such as Green Light Optimal Speed Advisory (GLOSA) [92], optimum route planner, and network traffic congestion control.

Due to the advancement of wireless networks, vehicles can connect with cloud infrastructures for accessing cloud services using OBU [93] in order to enhance the network connectivity. The OBU may have the capability to use Long Term Evolution (LTE) network. The vehicles' vendors can make a contract with the nation-wide wireless network providers to install cloud services into their vehicles to enhance vehicle's safety, performance, reliability, etc [94]. Furthermore, RSUs may connect with cloud infrastructure for getting different cloud services such as Software as a Service (SaaS), Platform as a Service (PaaS), and Infrastructure as a Service (IaaS) [93]. However, the communication procedures between vehicles and cloud infrastructures experience higher transmission delay than other V2V or V2I communication procedures and the communication cost is high.

c) *Vehicular Networks.*
In an autonomous vehicular system's communication network, there are two main issues to handle:

- Message dissemination among vehicles inside or outside of the communication range,
- Better communication schemes for V2X (V2V and V2I).

In an autonomous vehicular system, vehicular communication can be divided into two main categories which are discussed

[1] While seven channels are allocated in the United States for DSRC, Europe has four channels [84].

[2] 1609.1-1609.4 / architecture, resource manager, security, networking, multi-channel operations, and 1609.11 / over-the-air data exchange protocol [85]

in the following subsections.

i) ***Vehicle-to-vehicle communication.*** In a highly dynamic environment, each vehicle in a single lane and follows a leader vehicle. Thus, to facilitate the stability of traffic system, each vehicle needs to periodically transmit its current position, velocity, and other information to its neighbor vehicles, which is called beacon message. To facilitate the continuous transmission of beacon messaging, several methods have been proposed which can be further categorized into two types: contention-free and contention-based. In the contention-free beacon message dissemination, vehicles are arranged in several groups and the communication slots are divided into different time slots, called Time Division Multiple Access (TDMA) [95], [96]. On the other hand, in contention-based methods, communication channel frequencies, signal power, channel window sizes are adjusted at run time to provide better packet delivery rates [97]–[100].

There are several efforts [101]–[103] that have been made to reduce the channel congestion of V2V communication network. Proactive and reactive controllers have been investigated for beacon congestion control system using distributed manner [101]. Here, the proactive controller estimates the desired transmission parameters using current neighbor vehicles and the reactive controller is the feedback-based controller to provide the robustness. In another work [103], a liner message congestion control technique has been presented where the packet transmission rate is controlled by using feedback messages from neighbor vehicles. However, this work is limited to the single-hop scenario (i.e., no intermediate message relay nodes), which means it does not work for ad-hoc network. The research work by Stanica et al. [102] presents the effects of contention window on inter-vehicle communication where the authors proposed several approaches to adjust the minimum congestion window based on vehicles density such that the performance of the IEEE 802.11p protocol would be improved.

CACC or platoon systems highly rely on V2V communications to maintain the stability of the system. There are other sets of works which use cruise control features to avoid the collision of the communication channel. For example, in the work [104], the leader vehicle first transmits the message to avoid the contention with other vehicles. Then, all other vehicles transmit messages based on TDMA approach where only leader vehicle is capable of communicating with other vehicles. Other vehicles can only communicate with its nearby neighbor vehicles. Amoozadeh et al. proposed a platoon based communication protocol where vehicles are connected through ad-hoc network [105]. In that approach, vehicles inside platoon can dynamically perform three types of maneuver: joining to platoon, leaving from platoon and lane changing for the entire platoon. For platoon maintenance, the proposed system uses vehicles' control logic considering intra-vehicle distance, speed, and acceleration of vehicles. Also, separate beacon message is designed and single hop message transmission is allowed to alleviate the communication cost of vehicles. Another work [106] uses the vehicles' relative position information with respect to the leader vehicle position to decide which vehicles can transmit messages at a particular time slot. In the work [107], the entire platoon is distributed into different regions based on the communication range of vehicles. One master vehicle is selected in each region to coordinate the message disseminations for collision avoidance and enlarging the platoon length as well. However, to ensure the connectivity of the whole platoon, packet retransmission is supported in the transmission layer.

In another work of platoon based vehicle ad-hoc network [108], connectivity probability is studied based on different parameter settings (e.g., vehicle density, the communication range of vehicles and RSU, inter-RSU distance, etc) to design a connectivity-aware MAC protocol. The proposed protocol works in multi-channel reservation based, and it considers both vehicles' density and connectivity state to adjust the transmission rate of the beacon message. To further ensure the safety of vehicles in a platoon, a multi-priority Markov model is used to analyze the performance of underlying network connectivity and packets belong to intra-platoon transmission are assigned higher priority if necessary. However, the work considers, the platoon formation is static and vehicles cannot leave or change the lane.

Reducing channel congestions in V2V communication is a challenging task where roadway traffic density is high and vehicles are always moving. It is an open research problem to design effective periodic messages or beacon transmission schemes for CAVs as it needs consideration of such a traffic condition which is always changing and the underlying communication channel is not stable or reliable.

ii) ***Vehicle-to-infrastructure communication.*** V2I communication in CAVs takes place to favor each vehicle to establish a stable communication network. Mainly, V2I communication involves vehicles and RSUs which communicate with each other. Usually, the transmission delay of V2V communication is much shorter but V2V communication is not reliable and stable as vehicles are always moving and the inter-vehicle distances are changing as well. Also, the transmission messages from a platoon system may experience signal interference with the messages from another platoon system if two platoon systems are close to each other or crossing each other. However, two platoon systems may share information about hazardous road conditions or upcoming traffic congestions, which is only possible if these platoon systems are nearby to each other. To mitigate these issues, there would be several DSRC-based RSUs installed in each traffic intersections so that vehicle can communicate with each other via RSUs if they are out of each other's communication range. In the work [109], the RSUs are used as forwarders to relay safety message between different group of vehicles. Abdrabou et al. [110] proposed the minimum number of RSUs for a particular road by considering the multi-hops packet delivery delay for V2I communication. Another similar work by Zhang et al. [111] presents the performance of uplink and downlink connectivity between vehicle and RSUs in ad-hoc mode. It also investigates the features of inter-RSUs distance, vehicle density, radio coverage and the maximum number of hops for connectivity between vehicles and RSUs.

Typically RSUs are equipped with 802.11p based DSRC device where IEEE 802.11p uses carrier sense multiple access with the collision avoidance (CSMA/CA) mechanism. Several research works try to address the issues of RSUs (i.e., high channel congestions) when vehicle density is too high. In a dense traffic scenario, the DSRC-based devices subject to exhibit poor performance with significantly increased packet loss and average delay [112]. In the work [112], a V2V message forwarding scheme is designed to extend the coverage range of RSUs, improve the link quality and maintain high throughput. It chooses the intermediate-destination vehicle node to forward the message based on platoon's velocity. Jia et al. [113] analyzed the uplink performance of drive-through Internet in feasible error-prone environments to propose a platoon-based cooperative retransmission scheme by jointly considering traffic mobility and wireless communication. In their approach, each vehicle helps to retransmit the data for its neighbors in the case of a transmission failure, and a 4-D Markov chain is formulated to model the cooperative retransmission behavior. Bi et al. [114] proposed an IEEE 802.11e based MAC layer protocol for V2I communication to guarantee a minimum delay for emergency messages while maintaining high QoS performance for other applications. Basically, in their work, there are several vehicles and RSUs are distributed randomly, they consider the busy tone signaling in MAC protocol to consider high priority for emergency applications. The communication channels are divided into two groups: busy tone channel and data channel. On the busy tone channel, the algorithm transmits channel jamming signals, which is called "busy tone". The proposed method can be applied to the autonomous vehicular system where vehicles can group together and one leader vehicle contacts with RSUs for receiving services.

In [115], platoon features are used to meet the Quality of Service (QoS) of vehicular applications. Based on the proximity of nearby vehicles, a group of vehicles forms a platoon system where different channels are used for inter-platoon and intra-platoon communications. A hierarchical optimization model is designed to maximize the utility of individual vehicle inside platoon and to minimize the cost of reserving a stand-by channel based on data transmission and collision threshold with licensed users. The connectivity probability of V2X is thoroughly investigated in the work [116] where the vehicles are Poisson distributed with different traffic densities. The work also includes the relationships between the connectivity probability and other parameters, (e.g, vehicle density, the transmission ranges of different elements in the network) to ensure the connectivity.

Furthermore, there are existing works [117]–[119] that consider vehicle-to-cloud communication networks. For example, the work [117] considers vehicle cloud models and data routing and dissemination techniques for the vehicular ad-hoc network. The vehicle cloud model is dynamic, created by cooperatively sharing available resources from vehicles and RSUs. Besides, it envisions vehicular cloud networking and encourages collaborations among cloud members (vehicles/RSUs) to provide advanced vehicular services. Due to its resource sharing properties, this work can be incorporated in autonomous vehicular systems where vehicles cooperate with each other. Another work [118] also discusses the opportunities to establish local vehicle cloud, road side vehicle cloud, and remote vehicle cloud based on V2X networks. Here, vehicles share resources with each other to create local vehicle cloud, road side vehicle cloud is created based on available resources of RSUs and remote vehicle cloud is resided some remote servers or data centers.

From above discussion, we can summarize that V2I communications and vehicles' mobility models are closely related to each other. Several previous studies have been proposed to tackle the poor performances of V2V communications caused by vehicles' mobility models using RSUs.

C. Future generation technologies

In this subsection, we present some promising future generation communication technologies for CAVs.

1) Visible Light Communication: Li-Fi is a wireless communication technology and it uses the band of visible light for data transmission. Li-Fi is faster than other wireless communication, is useful in secure communications as light cannot penetrate the walls, and is cheap, as LED lights are used for data transmission. The data transmission is carried out by LEDs' flickering states. Due to vision persistence of human eyes, Li-Fi data transmission is not undetectable for human. Different strings of 0's and 1's can be decoded to retrieve the transmitted information. A LED can act as a sender and a silicon photo diode can act as a receiver. Different data modulation techniques are used for Li-Fi devices to achieve data transmission range up to 40 Mbits/s [120]. Li-Fi typically uses visible light between the wavelength 780 nm and 375 nm.

The cost of Li-Fi is less than other communication techniques as LEDs have been commonly used in automotive lighting [121]. In contrast to the typical V2V communication strategy, the work [122] studies the feasibility of visible light communication strategy based on Bit Error Rate (BER) showed poor performance in the presence of longer inter-vehicle distance, background noise, incidence angle, and receiver's electrical bandwidth. In the method, the vehicle's rare light modules are used as a communication module and the authors evaluated the proposed method by using communication channel's DC gain model, noise model with vehicles' trajectory control theory. In [123], bi-directional Li-Fi transceiver is implemented using edge emitted laser diode and silicon photo diode for short range data communication. Based on the implementation, data transfer can be operated in full duplex mode at 120 Mbits/s. Li-Fi transceiver is also proposed for V2V communication based on 802.11 MAC protocol [124].

2) LTE Advanced Pro: LTE Advanced Pro (LTE-A) is the evolutionary path from LTE Release 14. LTE-A provides access to a wide range of packet-based telecommunication services including advanced mobile services.. The goal is to reduce the transition time from idle to connected mode from 100 ms in LTE to less than 50 ms in LTE-A. Similarly, the transition from dormant connected node to active connected node should be reduced from 50 ms in LTE to less than 10 ms in LTE-A. Radio communications have already been identified as a way of improving road safety and traffic flow efficiency, and radio communications are instrumental in enabling the deployment of CAVs. To support these as well as many other applications, the 3rd Generation Partnership Project is developing an ITS solution based on LTE targeting different V2X scenarios, including V2V, V2I, vehicle-to-pedestrian (V2P), and vehicle-to-network (V2N). LTE V2X intends to reuse the higher layers and services, and hence specify only the lower layers. An LTE solution will be able to utilize the existence of an already deployed network infrastructure to support many of the use cases and provide an increased level of security for distributed systems. The Technical Report [125] being produced by the feasibility study includes a wide range of categories characterizing the service requirements: such as authentication (how to authenticate the V2X users/UEs), capacity, service charging (how mobile operators should charge for the use of V2X service), and so on.

In next section, we discuss the human factors involved in the design process of CAV systems.

IV. Human Factors

Every year, thousands of people die from traffic incidents and the major contributing factor identified in numerous studies is diver errors. To encounter and support driver mistakes/limitations such as long reaction time to unexpected/expected roadway events [11], distracted driving [12], and driving under influence [13], modern vehicles are equipped with advanced driver assistance systems such as forward collision warning, lane keeping assistance, blind spot warning to name few. However, new features such as entertainment system, hand held devices (e.g., smart phone and tablet), navigation system create new form of distracted driving and been reported as the primary cause of thousands of crashes. While intervention of more technology is future vehicle models are unavoidable, the promise of fully automated vehicle is that drivers do not need to control the vehicle and most of human mistakes and driver distractions could be eliminated by autonomous vehicle control system. The feedback between vehicle's operational environment and associated driver behavior follow a complex pattern [14]. While understanding driver behavior and modeling is recognized as a complex issue in traditional vehicles, it is also a key challenge for autonomous vehicle design [15]. Thus, the interactions between human and vehicle have been a core research focus from automobile industry and academia as user acceptance is the vital challenge for mass acceptance. To accomplish this objective, it is imperative to understand human behavior in designing key features CAV systems, navigation algorithms, and reliable human-machine interface.

The mass adaptation of CAVs largely depends on the how the autonomous system can be designed based on the human factors, such as user expectation, ride comfort, and trust on automated system [51], [126]. The report entitled *Human Factors' Aspects in Automated and Semi-Automatic Transport Systems: State of the Art* identified major human factor issues, which are: acceptance and comfort, situational awareness, loss of skill, behavioral adaptation and risk compensation, workload, level of automation, and normal transitions, responses to system failures, usability, and guidelines [127].Human factors consideration for CAV can be broadly categorized into two groups: i) design CAV system considering user expectation, and ii) adapt to the CAV system by the user (as shown in Figure 4). The considerations for human drivers' expectation in designing the CAV system can be further classified into two sub-groups: a) user comfort and acceptance and b) user trust. On the other hand, users of the CAV system need to adapt the engineered and designed CAV system, which includes a) behavioral adaptation and b) situational awareness. An overview of human factors' consideration in CAV design is illustrated in Figure 4 and discussed in the following subsections.

A. Design CAV System Considering User Expectation

Understanding how human will interact with the autonomous system is an important research focus of CAV system. Satisfying user requirements in terms of comfort, workload, perception-reaction, and maintaining safety are extremely critical in designing the safe and reliable CAV. This subsection provides detail review on the user comfort and acceptance, and trust of the CAV systems.

1) User comfort and acceptance: User comfort experienced in a CAV system will be an important factor in terms of user acceptance. A CAV controller operates the longitudinal (i.e., car-following mode) and lateral movement (i.e., lane-changing mode) of a vehicle, and must replicate a human driving experience in each CAV where expectations of a user for comfortable driving experience is not violated. Longitudinal driving behavior model (i.e., car-following model) and lateral driving behavior model (i.e., lane changing model) capture human driving behaviors in different driving environments. Car-following model represents driver's reactions to the surrounding environment in the car-following mode. Car-following mode must ensure acceptable vehicle dynamics (i.e., maximum speed, maximum acceleration/deceleration) and string stability (i.e., sharp fluctuations of position, speed, and acceleration/deceleration) while CAVs are in a traffic stream to improve user acceptance, comfort, and safety. Car-following models capture how a subject vehicle follows the preceding vehicle by maintaining longitudinal position and minimum gap, and driver's reaction for the longitudinal movement of a vehicle. The acceleration/deceleration behavior of a CAV's car-following model must maintain comfortable accelerations/decelerations in different driving conditions. Thus, car-following behavior for the longitudinal movement needs to be examined in three different acceleration/deceleration scenarios for the CAV controller design: i) no acceleration/deceleration (uniform speed) with time, ii) a constant deceleration with time, and iii) a constant acceleration with time [128].

Different existing car-following models, which capture human driving behaviors, can be examined for a CAV controller design for longitudinal movement control to achieve user comfort and acceptance of a CAV system. The general form of car-following models assumes that each driver reacts to a stimulus, which leads to an actuation of the acceleration/deceleration [129]. Many car-following models, such as the Gazis-Herman-Rothery (GHR) model, the Collision Avoidance (CA) model,

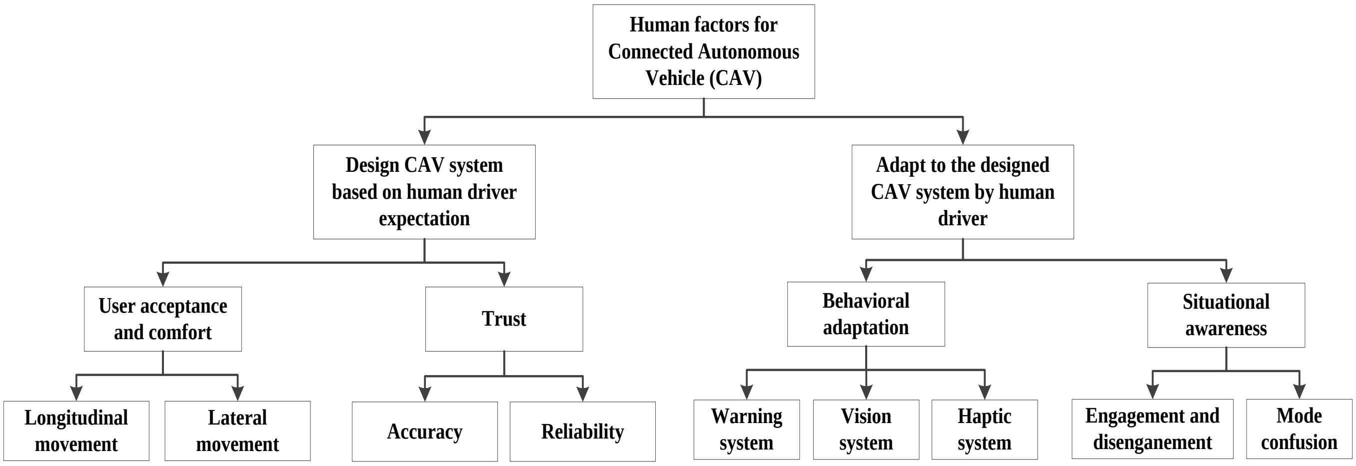


Fig. 4: Human factors for connected autonomous vehicles.

the Helly model, the Fuzzy Logic based model, the Optimal Velocity (OV) model, and the Meta model, have been developed since the 1950s [129]. Despite the substantial research related to GHR model dating to 1958, the many contradictory findings regarding the correct parameter selection have resulted in substantially less GHR follow-up work [10]. It calculates a speed with a safe space-headway to avoid collision with the preceding vehicle. The Helly model, also known as the linear model, was developed based on the GHR model [130], and relates the acceleration of the follower vehicle to the desired trailing distance. Although the Helly model fits well with observed data, the calibration of model parameters is the main difficulty because of a large set of parameters [131]. In the 1990s, the fuzzy logic theory was introduced to model car-following behaviors to better consider the fuzziness in drivers' decision-making processes [132]. The fuzzy rules capture the reactions of a driver to the actions of other drivers based on a set of driving rules developed through experience. Thus, fuzzy logic based car-following model could capture the CAV users' characteristics for the car-following mode. In the OV model, the acceleration/deceleration of a subject vehicle is represented by the function of the difference from the optimal speed and driver sensitivity. The uniqueness of this model is that it can capture the car-following behavior of a CAV at different levels of traffic congestion (i.e., congested condition) [133]. Wiedemann proposed a psychophysical car-following model [134] based on a perceptual threshold of the driver to model different types of driving (e.g., free driving, emergency driving). In this model, the perceptual threshold of the CAV users for each driving condition depends on the gap and the relative speed between the subjectand the preceding vehicles, and assumes that CAV will react when they reach these thresholds. Gipps proposed a multi-regime car-following model for congested and free-flow traffic conditions [135]. The maximum acceleration of these traffic conditions being determined based on two constraints: i) the drivers desired speed, which is the maximum speed limit; and ii) the minimum space-headway, which is required to avoid collisions. The second constraint precludes the occurrence of accidents and tends to produce overly safe behaviors for the CAV users when compared to actual car-following movement in traffic. Yang and Koutsopoulos presented a multi-regime model, which also precludes incident-inducing car-following mode [136]. The Intelligent Driver Model (IDM) is another multi-regime model, which captures the dynamics of different traffic congestion level more realistically than any other models [137]. According to this model, the acceleration of a subject CAV can be designed based on the subjectCAV's speed, the ratio of current gap and desired gap between subject and the preceding CAVs, and the relative speed between the subject and preceding CAVs. This car-following model was used as in car-following mode controller for the vehicle automation for CACC system design. For example, Milanes and Shladover developed three different control systems to evaluate the performance of CACC controller with the IDM in 2014: i) ACC system with field data, ii) CACC control systems with field data, and iii) CACC control systems using the IDM [138]. Field experiments were performed with production vehicles to evaluate these three controllers. The actual responses of the vehicles and users were measured, and it was found that the IDM model demonstrated comfortable car-following behavior than the other controllers. However, the IDM model shows slower response and large space-headway between CACC vehicles. The critical factors considered in existing car-following models are identical: the subject vehicle's own speed difference, the distance between the subject vehicle and the one it follows, and driver's reaction time [128]. It is required to evaluate vehicle dynamics and string stability of these car-following models to assess the user comfort and acceptance. The following paragraph introduces the existing lane-changing methods and discusses the limitations and challenges of these models in designing the CAV systems.

Merging to and diverging from a lane is related to lane changing behaviors of a CAV user. For example, as a CACC system (full vehicle automation) allows a minimum space-headway between vehicles; it becomes very challenging for a vehicle to join an existing platoon at any location other than at the beginning or end of the platoon [139]. Similarly, a vehicle attempting to leave a platoon will likely need to adjust its desired speed and gap depending on the user preferences and comfort to prepare to move to an adjacent lane. User of a CAV will not be comfortable during lane changing and lane-changing modeling must replicate user preferences considering the modeling of user characteristics, such as the variability of CAV user behaviors across different user types (i.e., younger/older and aggressive/non-aggressive drivers), users gap acceptance behavior, and gap availability in the target lane [140], [141]. In terms of vehicle's lateral movement control, numerous researches proposed different models in terms of modeling lane-changing behavior. Chee and Tomizuka compared linear quadratic (LQ) controller, frequency shaped linear quadratic optimal control (FSLQ) as well as the sliding mode controller for the tracking of the human replicated lane-changing trajectory [142]. Wang et al. determine optimal lane change times and accelerations by minimizing an objective function, which considers driving safety, efficiency and comfort criteria for connected autonomous vehicle. They included driver comfort by penalizing large accelerations or decelerations for strategic overtaking and cooperative merging scenarios [51]. Hatipolglu et al. proposed a nonlinear controller to track the desired yaw angle with consideration of the vehicle dynamics and the actuator dynamics [143]. In addition, both radar and vision camera are used to detect the road curvature. Later, Kosecka et al. used a vision based lateral control system to investigate system parameters, such as vehicle velocity, and look ahead range of a vision sensor, and the perception and control delay associated with the system [144]. They tested three feedback control strategies on the lateral control task with an experimental vehicle. These strategies show acceptable performance in terms of replicating lane-changing comfort on the straight and curved roadway sections. Keviczky et al. used model predictive control (MPC) to minimize the tracking errors as well as the control input for the lane-changing behavior [145]. The experimental simulation result shows that the MPC controller can have a good stability performance under the high velocity. Naranjo el. al. adopted Fuzzy logic based controller to imitate the human decision about when to manipulate the lane changing behavior based on the headway and velocity difference between subject vehicle, and preceding and following vehicles in a target lane [146]. The fuzzy lateral movement controller captures human driving behavior using the experts' procedural knowledge and different linguistic values. One of the biggest challenges of the lateral motion control such as the lane changing and overtaking is to detect the environment and predict the intentions of the neighbor vehicles. The sensing capability of a sensor must be very accurate if the distance between two vehicles is very short [147]. Moreover, since the merging action is an interaction between the subject vehicle and the vehicles in the adjacent lane, it is crucial to know the intention of the neighbor vehicles. Any failures in these two aspects will lead to a catastrophic result, such as the instability of the vehicle dynamic [148]. In dealing with high crash risk, conservative algorithm is developed to deal with the uncertainties (in sensor data, capability, and response of a CAV impose conservative limits on the acceleration, deceleration, and steering decision of a CAV), which will heavily deteriorate the efficiency of the lateral motion generation, and user comfort and acceptance [149]. While the emergence of V2V and V2I communication technologies (discussed in Section III) can help to solve these uncertainties as well as the inefficiency [150]. It is already shown using the simulation that the CACC system, which uses communication among the vehicles, will increase the performance of the controllers in terms of user safety, user comfort, and traffic efficiency aspects (i.e., the capacity of a roadway) [51]. In more complex scenarios, such as the intersection lane-changing behavior, the lateral controller with V2V and V2I functions obviously outperform the conventional prediction based controller.

2) Trust: To realize full benefit of the CAVs, autonomous system must earn human trust so that people can rely on the system. Any autonomous system needs a high level of trust to mass adoption of the technology [151]. The trust of an autonomous system can be measured with the system accuracy [152] and reliability [126]. Lee and Lee found that high false alarm rate (i.e., accuracy) decreases the system reliability and compliance of an autonomous system [153]. Moreover, Seppelt and Lee found that it is more effective to provide continuous information to the users regarding the state of an autonomous vehicle instead of providing immediate warning because of system failures [154]. One needs to understand trust factors for providing guidance to the CAV system developers. Carlson et al. identified twenty-nine factors that can compromise trust of CAV user, and performed statistical analyses for autonomous vehicle related factors, and implications of safety criticality on trust factors [155]. The critical factors identified for user's desirability and reliability of the autonomous cars are: i) level of accuracy of the vehicle's routes; ii) amount of current roadway information available to the vehicle (e.g., weather, traffic congestion, construction, etc.); iii) effectiveness of the vehicle's training and prior learning; iv) system failure detection (e.g., making a wrong turn, running a stop light); v) accuracy of the route selection; vi) user's familiarity with the vehicle features; vii) agreement of routes between vehicle and user's knowledge; viii) the vehicle's methods of information collection [155].

B. Adapt to the Designed CAV System by User

Behavioral adaptation and situational awareness are summarized in the following sub-sections.

1) Behavioral adaptation: In CAV system, Human-Machine Interface (HMI) plays a critical role as HMI assist user to change user's role from an actuator to a supervisor or vice-versa [127], [156]–[158]. A user needs to adapt to HMI interface of a CAV to execute appropriate decisions through voice command, touch or any other haptic (i.e., gesture) command. It is warranted to increase CAV user education about the system functionality and limitations of an autonomous vehicle [159]. If users are more knowledgeable about the system and their limitations, users will be more aware of such system and they will adapt to the system [160]. In addition, a user will act as a sensor in a CAV system and could provide input to the system controller depending on the different driving scenarios (e.g., congested/uncongested roadway traffic condition, merging or diverging traffic scenario). Recently, gesture based automated interface has been explored using different sensor technologies for vehicle control, primarily for autonomous vehicles [161]. When an occupant or a user is unable to interact with the CAV system through voice or touch interface, a gesture-controlled system could be very effective [156]. CAV vehicle user performs a gesture (e.g., the motion of hand), and CAV can interpret and react in a manner that is commensurate with the users' intentions. Thus, it is critical to design such gesture controlled CAV system, which is easy to replicate, produce repeatable results, comprehend, and minimize the pain of learning gestures for the user. With advancing the vehicle technology, we need to study in-depth how human will interact with automation features, such as how to minimize user introduced errors, consequences of over or under relying on the system, minimization of the impact of the drivers reduced workload, and effectiveness of different driver feedback system interfaces.

2) Situational awareness: Situational Awareness can be defined as the awareness of a user regarding the surrounding environments in a CAV system. It has been suggested that automation may lead to user not informed with the surrounding situations and hence loss of situational awareness [162]. Endsley defines situational awareness as user's constant attention on events what are going on around in a dynamic human decision-making environment, and based on the current information one also needs to forecast near future events [163]. If we consider a CAV system, a user needs to be aware of surrounding dynamic environment and needs to perform an action based on an extreme emergency (e.g., system failure of a CAV). According to Endsley, situational awareness of a dynamic human decision-making environment can be divided into three levels that includes: the perception of the status, the attributes, and the dynamics of the relevant situation elements; the comprehension level, involves integrating the different situation elements to a holistic picture of the situation resulting in the comprehension of the meaning of the different elements; the generation of assumptions about the future behaviors of the elements on the basis of the comprehension of the situation [163]. CAV system needs to be designed in such a way so that the system can provide information to the user in a regular interval to take any action in a timely manner on a critical situation (e.g., system failures). Situational awareness for the CAV system can be divided into two categories: i) engagement and disengagement; and ii) mode confusion. As a user of a CAV system, a passive fatigue (e.g., decreased driving task engagement) may occur due to engaging and disengaging with this system. Such sudden shifts in vehicle operation can require long reaction time during safety-critical driving events, such as roadway incidents. The effect of automation on driving behavior as it relates to how a user in a CAV environment will react during engaging and disengaging, and procedures to facilitate reliable and safe transition have not been studied yet. Because of automation (workload reduction), CAV users will engage in non-driving related tasks that can distract a user from the supervising role, which will lead to risky situations in case of system failures and emergencies. On the other hand, mode confusion is a phenomenon that can be defined as a discrepancy between the driver expectation from a designed CAV to operate the system and the actual operation procedure of a CAV [164]. It is a sense of confusion concerning which aspects of vehicle performance is controlled by the user and which is controlled by the automation at a particular instance [165]. If a user of a CAV is not aware of the state of the vehicle, a user could make decisions based on the certain belief, which is not correct [166]. Therefore, to study the effects of stimulus-independent thought, which could occur before, during and/or after a transition, it is a critical need to develop a suitable method to establish what mechanisms contribute to the situational awareness to a CAV user go from being engaged with the control of the vehicle during automation to being disengaged in case of system failures.

In next section, we discuss the possible future research challenges and directions on three key factors of CAV systems.

V. CAV Challenges and Future Research Directions

Identifying the impacts of three different factors (controller, communication, and human factors) on fully autonomous vehicular systems is necessary. Currently, there are many works seeking to establish the fully autonomous vehicular systems by analytical and experimental studies. Further advancement of fully autonomous vehicular systems depends on the future research trends of different aspects of vehicular communication, controller design, and human acceptance with their interjections. In this section, we introduce critical future research directions for the advancement of fully autonomous vehicular systems.

A. Intelligent Controller Design

Although the current autonomous car controllers work well to fulfill various control objectives, there is still much room left for further research. In the following paragraph, major controller challenges in intelligent controller design are proposed to show the potential directions for future works.

Centralized versus distributed control: It has been demonstrated that centralized control that manipulates multiple vehicles simultaneously can maximize overall traffic benefits [29]. However, the control authority of each individual vehicle is still important with respect to the liability issue and human acceptance [167]. In addition, communication and computation capabilities are highly demanding in the realization of centralized control, which is still challenging in the near future. As a result, how to incorporate the centralized traffic management with distributed control in each individual autonomous vehicle is an important future research direction. This has the potential to increase reliability of the CAV system. In addition, the loss of the human authority can be mitigated by the involvement of the distributed control.

Consideration of communication imperfection: Both the centralized control and distributed control of the autonomous car can have plenty of information to realize the task, such as stabilization and optimization, via V2X communication. However, most of the research just assume perfect communication scenario, especially for optimization purpose [51], which is unrealistic and hence the results are debatable. As a result, how to consider the communication effects, such as delay, shadow fading, and interference, on the optimization algorithm should be a critical topic under current communication capabilities.

Hence, how to incorporate the compensation of these communication imperfection will determine the adoption of these advanced algorithms.

Mixed traffic scenario: The existence of the cars without communication capability in the traffic will challenge the design of the connected and autonomous controller. Without V2I communication capability, the vehicles cannot broadcast the information to the centralized controller. Hence, the optimization resulted from the centralized controller will be deteriorated. In addition, the distributed cooperative controller will degrade to the sensor-based controller, which sacrifices efficiency. As CAVs will penetrate the market gradually [168], the coexistence of the connected vehicles and conventional vehicles should be expected. Then, how to design a control scheme that can be flexible enough to be applied in mixed traffic is another crucial topic.

B. Vehicular Communication

The advancement of communication architectures makes it possible to support safety applications for existing transportation systems. However, current vehicular communication is still not ready to ensure stability and safety of a well maintained fully autonomous vehicular system. The uncertainty of traffic conditions would hinder reliable and continuous connectivity of V2X communications. Besides, network security is crucial for the safety of traffic environment. Several future research directions for fully autonomous vehicular systems are introduced as follows.

Heterogeneous vehicular communication: To provide comfort and ensure safety, both V2V and V2I communications are required. IEEE 802.11p-based DSRC communication is the backbone of the existing vehicular communication and it works well for static fully autonomous vehicular systems. However, the limited coverage of RSU units brings the necessity of heterogeneous vehicular communications. The research underway into heterogeneous network standards may form the basis for future ITS applications. The heterogeneous communication protocols and schemes should be robust and scalable to deal with the uncertainty of traffic conditions. The resource scheduling unit should consider application criteria, synchronization, and a context-aware mechanism to provide more dependability of heterogeneous communication links for fully autonomous vehicular systems. Current transmission control protocol should be customized to be suitable for robust and highly scalable data dissemination scenarios.

Security and privacy in vehicular communication: The heterogeneous connectivity of vehicles inside an autonomous system demands strong security mechanisms to prevent unwanted access to vehicles' control. Messaging between vehicular systems would be received, tempered or altered by malicious nodes. The centralized certification revocation in autonomous systems would cause longer delay and interrupt the sporadic connections between leader and follower vehicles. Further research should consider developing security architecture to support heterogeneous network architecture considering reliability and QoS of autonomous systems. The combination of physical and application layer security mechanisms might be useful to reduce the overhead to impose the security of autonomous systems. Besides, the architecture should support the anonymity of vehicles outside of autonomous vehicular systems such that personal information can not be identified. The data encryption mechanisms considering computing resource, time, and network architecture would be a research direction to follow.

Signal interference avoidance: The signal interference avoidance for both safety and regular beacon messaging in congested situations is critical research direction to increase the reliability autonomous vehicular systems. The optimized V2V channel access mechanisms should be considered to satisfy stringent latency requirements. There are already a lot of theoretical works consider efficient channel allocation mechanisms based on message sending rate, duration of contention windows, channel switching delay, successful message reception rate, channel busy ratio, throughput, packet error rate, etc. However, the channel allocation mechanisms should be evaluated and verified in different real world roadway traffic scenarios considering uncertainty nature of vehicular communication in fully autonomous vehicular systems.

C. Human Factors

A primary goal of the most automation is to achieve a high reliability. For the CAV system to be acceptable, user preferences must be met. In previous Section IV, current state-of-the-art understanding of human factor issues, research trends and challenges are discussed about human factors related to a CAV. In this sub-section, we identify future research directions on major human factor issues, which include: i) User preferences; ii) Engaging and disengaging in different roadway traffic events; and iii) Human-machine interface.

CAV user preferences modelling using artificial intelligence: User in each vehicle of a CAV will have different preferences, such as preferred speed, gap between vehicles, in different driving condition [169]. Thus, a CAV must allow different driving preferences (e.g., speed, acceleration) based on the user characteristics such as age (young, older) and gender (male or female). One of the major challenges of the CAV system is how to incorporate these user preferences in the real-time CAV operation. A machine learning-based model can be developed for human-centered CAV speed recommender system depending on the human behaviors. It is possible to train different user behaviors with collected vehicle trajectory data for a comfortable speed, acceleration, and the gap from the immediate front vehicles. In addition, the modeling of lane changing (merging and diverging) behaviors depends on the modeling accuracy of user preferences, such as user gap acceptance behavior, and available gap for changing lane in the target lane. Thus, it is a critical need to develop a user oriented merging and diverging models by incorporating human preferences within the CAV system.

Engaging in the case of CAV's system failure: CAV users will only require engaging in a supervisory role if there is a safety-critical situations in the case of CAV system failures. However, users' ability to do so is limited by humans' capacity for staying alerted when disengaged from the driving task. Manufacturers and other entities need to incorporate users engagement monitoring system for a CAV system. Therefore, it is a critical need to develop a suitable method, such as integration of different warning system (e.g., visual, audible and vibration warnings) to increase awareness of a critical situation so that CAV users can be engaged in the system to control the situation.

Integration of multiple assistance systems in the HMI: HMI plays a critical role to inform and take an appropriate decision through touch and voice command or any other gesture command. Thus, it is important to study in-depth how human will interact with automation features. At a minimum, HMI interfaces of a CAV system should be capable of functioning reliably and providing accurate information (e.g., a malfunction of the CAV system) to the user [170]. We also need to investigate how we can integrate multiple assistance systems in the HMI so that we can ensure the reliability of the system. At the same time, user distraction and overload need to be reduced for increasing the user acceptance in case of CAV system failure [171].

VI. Conclusion

CAV can improve the safety significantly by the reducing human error of manual driving. The authors conducted an in-depth review of three key factors (i.e., communication-aware controller design, sensing and communication technologies, and human factors) related to the design of CAV systems, as these factors are essential components for designing reliable and trustworthy CAVs. Based upon the critical review, the need of each key factor, current practices, and challenges for designing a CAV system have been identified. It is clear that the sensing and communication technologies can realize the better autonomous vehicles since more information can be used to improve the controller efficiency and realize a better performance in dealing with the uncertainty of the roadway traffic conditions. In addition, V2I communication can further contribute to establishing the centralized controller, where global optimization can benefit the overall traffic condition. It is expected that this paper would motivate the design of more advanced interdisciplinary technologies that integrate those from the three key areas for CAVs. It is very important to ensure the full utilization of heterogeneous sensing and communication technologies to improve the safety and comfort of the CAV systems. In order to fully utilize the vehicle automation, there must exist a certain level of user acceptance between the user and the AV technology. Finally, future research should be devoted to further elaborating several major future research areas, such as delay effect on controller operations, mixed traffic challenge for the information topology design, hybrid sensing and communication technologies, user preferences, engaging and disengaging in different roadway traffic events, and HMI, for the CAV systems.

References

[1] P. Ioannou, *Automated highway systems*, 2013.

[2] J. M. Anderson, K. Nidhi, K. D. Stanley, P. Sorensen, C. Samaras, and O. A. Oluwatola, *Autonomous vehicle technology: A guide for policymakers*, 2014.

[3] S. Mahan, "Self driving car test," *Internet: http://www.google.com/about/jobs/lifeatgoogle/selfdriving-car-test-steve-mahan. html,[Jun. 15, 2013]*.

[4] "Deployment of autonomous vehicles for public operation," 2017, https://www.dmv.ca.gov/portal/dmv/detail/vr/autonomous/auto.

[5] B. W. Smith, "Sae levels of driving automation," *CIS: SLC*, 2013.

[6] "No need for speed: More innovation needed before adopting automated vehicles," 2016, http://www.robotictips.com/no-need-speed-innovation-required-adopting-automated-vehicles/.

[7] "Three-quarters of americans "afraid" to ride in a self-driving vehicle," 2016, http://newsroom.aaa.com/2016/03/three-quarters-of-americans-afraid-to-ride-in-a-self-driving-vehicle/.

[8] "Tesla crash report," 2016, http://fortune.com/2016/09/15/tesla-autopilot-crash-china/.

[9] M. Elbanhawi, M. Simic, and R. Jazar, "In the passenger seat: investigating ride comfort measures in autonomous cars," *IEEE ITSM*, vol. 7, no. 3, 2015.

[10] C. Andersen, "Linking drivers and roads," *PR*, vol. 76, no. 4, 2013.

[11] W. H. Teichner, "Recent studies of simple reaction time." *Psychological Bulletin*, vol. 51, no. 2, 1954.

[12] F. A. Wilson and J. P. Stimpson, "Trends in fatalities from distracted driving in the united states, 1999 to 2008," *AJPH*, vol. 100, no. 11, 2010.

[13] R. A. Shults, R. W. Elder, D. A. Sleet, J. L. Nichols, M. O. Alao, V. G. Carande-Kulis, S. Zaza, D. M. Sosin, R. S. Thompson, T. F. on Community Preventive Services *et al.*, "Reviews of evidence regarding interventions to reduce alcohol-impaired driving," *AJPM*, vol. 21, no. 4, 2001.

[14] N. Rashevsky, *Neglected Factors in Highway Safety*, 1966.

[15] C. C. Macadam, "Understanding and modeling the human driver," *VSM*, vol. 40, no. 1-3, 2003.

[16] T. L. Willke, P. Tientrakool, and N. F. Maxemchuk, "A survey of inter-vehicle communication protocols and their applications," *IEEE CST*, vol. 11, no. 2, 2009.

[17] G. Karagiannis, O. Altintas, E. Ekici, G. Heijenk, B. Jarupan, K. Lin, and T. Weil, "Vehicular networking: A survey and tutorial on requirements, architectures, challenges, standards and solutions," *IEEE CST*, vol. 13, no. 4, 2011.

[18] K. C. Dey, L. Yan, X. Wang, Y. Wang, H. Shen, M. Chowdhury, L. Yu, C. Qiu, and V. Soundararaj, "A review of communication, driver characteristics, and controls aspects of cooperative adaptive cruise control (cacc)," *IEEE Trans. on ITS*, vol. 17, no. 2, 2016.

[19] N. H. T. S. Administration *et al.*, "Preliminary statement of policy concerning automated vehicles," *Washington, DC*, pp. 1–14, 2013.

[20] V. Milanés, D. F. Llorca, B. M. Vinagre, C. González, and M. A. Sotelo, "Clavileño: Evolution of an autonomous car," in *Intelligent Transportation Systems (ITSC), 2010 13th International IEEE Conference on*. IEEE, 2010, pp. 1129–1134.

[21] J. Levinson, J. Askeland, J. Becker, J. Dolson, D. Held, S. Kammel, J. Z. Kolter, D. Langer, O. Pink, V. Pratt *et al.*, "Towards fully autonomous driving: Systems and algorithms," in *Intelligent Vehicles Symposium (IV), 2011 IEEE*. IEEE, 2011, pp. 163–168.

[22] R. Nagel, S. Eichler, and J. Eberspacher, "Intelligent wireless communication for future autonomous and cognitive automobiles," in *Intelligent Vehicles Symposium, 2007 IEEE*. IEEE, 2007, pp. 716–721.

[23] G. Leshed, T. Velden, O. Rieger, B. Kot, and P. Sengers, "In-car gps navigation: engagement with and disengagement from the environment," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 2008, pp. 1675–1684.

[24] S. Kammel, J. Ziegler, B. Pitzer, M. Werling, T. Gindele, D. Jagzent, J. Schröder, M. Thuy, M. Goebl, F. v. Hundelshausen *et al.*, "Team annieway's autonomous system for the 2007 darpa urban challenge," *Journal of Field Robotics*, vol. 25, no. 9, pp. 615–639, 2008.

[25] A. Bacha, C. Bauman, R. Faruque, M. Fleming, C. Terwelp, C. Reinholtz, D. Hong, A. Wicks, T. Alberi, D. Anderson *et al.*, "Odin: Team victortango's entry in the darpa urban challenge," *Journal of Field Robotics*, vol. 25, no. 8, pp. 467–492, 2008.

[26] S. Fontanelli, E. Bini, and P. Santi, "Dynamic route planning in vehicular networks based on future travel estimation," in *Vehicular Networking Conference (VNC), 2010 IEEE*. IEEE, 2010, pp. 126–133.

[27] J. Pan, M. A. Khan, I. S. Popa, K. Zeitouni, and C. Borcea, "Proactive vehicle re-routing strategies for congestion avoidance," in *Distributed Computing in Sensor Systems (DCOSS), 2012 IEEE 8th International Conference on*. IEEE, 2012, pp. 265–272.

[28] M. Wang, H. Shan, R. Lu, R. Zhang, X. Shen, and F. Bai, "Real-time path planning based on hybrid-vanet-enhanced transportation system," *IEEE Transactions on Vehicular Technology*, vol. 64, no. 5, pp. 1664–1678, 2015.

[29] A. M. de Souza, R. S. Yokoyama, G. Maia, A. Loureiro, and L. Villas, "Real-time path planning to prevent traffic jam through an intelligent transportation system," in *Computers and Communication (ISCC), 2016 IEEE Symposium on*. IEEE, 2016, pp. 726–731.

[30] D. R. Choffnes and F. E. Bustamante, "An integrated mobility and traffic model for vehicular wireless networks," in *Proceedings of the 2nd ACM international workshop on Vehicular ad hoc networks*, 2005.

[31] T. V. Mathew and K. K. Rao, "Introduction to transportation engineering," *Civil Engineering–Transportation Engineering. IIT Bombay, NPTEL ONLINE, http://www. cdeep. iitb. ac. in/nptel/Civil% 20Engineering*, 2006.

[32] C. Urmson, J. Anhalt, D. Bagnell, C. Baker, R. Bittner, M. Clark, J. Dolan, D. Duggins, T. Galatali, C. Geyer *et al.*, "Autonomous driving in urban environments: Boss and the urban challenge," *Journal of Field Robotics*, vol. 25, no. 8, pp. 425–466, 2008.

[33] D. Ferguson, T. M. Howard, and M. Likhachev, "Motion planning in urban environments: Part ii," in *Intelligent Robots and Systems, 2008. IROS 2008. IEEE/RSJ International Conference on*. IEEE, 2008, pp. 1070–1076.

[34] D. Kim, S. Moon, J. Park, H. J. Kim, and K. Yi, "Design of an adaptive cruise control/collision avoidance with lane change support for vehicle autonomous driving," in *ICCAS-SICE, 2009*. IEEE, 2009, pp. 2938–2943.

[35] R. Kala and K. Warwick, "Motion planning of autonomous vehicles in a non-autonomous vehicle environment without speed lanes," *Engineering Applications of Artificial Intelligence*, vol. 26, no. 5, pp. 1588–1601, 2013.

[36] S. Andrews, "Vehicle-to-vehicle (v2v) and vehicle-to-infrastructure (v2i) communications and cooperative driving," in *Handbook of Intelligent Vehicles*. Springer, 2012, pp. 1121–1144.

[37] D. Caveney and W. B. Dunbar, "Cooperative driving: beyond v2v as an adas sensor," in *Intelligent Vehicles Symposium (IV), 2012 IEEE*. IEEE, 2012, pp. 529–534.

[38] C. Roncoli, M. Papageorgiou, and I. Papamichail, "Traffic flow optimisation in presence of vehicle automation and communication systems–part ii: Optimal control for multi-lane motorways," *Transportation Research Part C: Emerging Technologies*, vol. 57, pp. 260–275, 2015.

[39] C. Roncoli, I. Papamichail, and M. Papageorgiou, "Model predictive control for motorway traffic with mixed manual and vacs-equipped vehicles," *Transportation Research Procedia*, vol. 10, pp. 452–461, 2015.

[40] H. Winner, S. Witte, W. Uhler, and B. Lichtenberg, "Adaptive cruise control system aspects and development trends," SAE Technical Paper, Tech. Rep., 1996.

[41] C.-Y. Liang and P. Huei, "String stability analysis of adaptive cruise controlled vehicles," *JSME International Journal Series C Mechanical Systems, Machine Elements and Manufacturing*, vol. 43, no. 3, pp. 671–677, 2000.

[42] R. Rajamani and C. Zhu, "Semi-autonomous adaptive cruise control systems," *IEEE Transactions on Vehicular Technology*, vol. 51, no. 5, pp. 1186–1192, 2002.

[43] J.-J. Martinez and C. Canudas-de Wit, "A safe longitudinal control for adaptive cruise control and stop-and-go scenarios," *IEEE Transactions on control systems technology*, vol. 15, no. 2, pp. 246–258, 2007.

[44] P. A. Ioannou, F. Ahmed-Zaid, and D. Wuh, *A time headway autonomous intelligent cruise controller: Design and simulation*. California PATH Program, Institute of Transportation Studies, University of California, Berkeley, 1994.

[45] L. Xiao and F. Gao, "Practical string stability of platoon of adaptive cruise control vehicles," *IEEE Transactions on intelligent transportation systems*, vol. 12, no. 4, pp. 1184–1194, 2011.

[46] S. E. Li, Y. Zheng, K. Li, and J. Wang, "An overview of vehicular platoon control under the four-component framework," in *Intelligent Vehicles Symposium (IV), 2015 IEEE*. IEEE, 2015, pp. 286–291.

[47] G. J. Naus, R. P. Vugts, J. Ploeg, M. J. van de Molengraft, and M. Steinbuch, "String-stable cacc design and experimental validation: A frequency-domain approach," *IEEE Transactions on Vehicular Technology*, vol. 59, no. 9, pp. 4268–4279, 2010.

[48] J. Ploeg, N. Van De Wouw, and H. Nijmeijer, "Lp string stability of cascaded systems: Application to vehicle platooning," *IEEE Transactions on Control Systems Technology*, vol. 22, no. 2, pp. 786–793, 2014.

[49] C. Desjardins and B. Chaib-draa, "Cooperative adaptive cruise control: A reinforcement learning approach," *IEEE Transactions on intelligent transportation systems*, vol. 12, no. 4, pp. 1248–1260, 2011.

[50] M. A. S. Kamal, J.-i. Imura, T. Hayakawa, A. Ohata, and K. Aihara, "Smart driving of a vehicle using model predictive control for improving traffic flow," *IEEE Transactions on Intelligent Transportation Systems*, vol. 15, no. 2, pp. 878–888, 2014.

[51] X. Wang and Y. Wang, "Human-aware autonomous control for cooperative adaptive cruise control (cacc) systems," in *ASME 2015 Dynamic Systems and Control Conference*. American Society of Mechanical Engineers, 2015, pp. V002T31A001–V002T31A001.

[52] L. Davis, "Effect of adaptive cruise control systems on mixed traffic flow near an on-ramp," *Physica A: Statistical Mechanics and its Applications*, vol. 379, no. 1, pp. 274–290, 2007.

[53] X.-Y. Lu, H.-S. Tan, S. E. Shladover, and J. K. Hedrick, "Automated vehicle merging maneuver implementation for ahs," *Vehicle System Dynamics*, vol. 41, no. 2, pp. 85–107, 2004.

[54] D. Marinescu, J. Čurn, M. Bouroche, and V. Cahill, "On-ramp traffic merging using cooperative intelligent vehicles: A slot-based approach," in *Intelligent Transportation Systems (ITSC), 2012 15th International IEEE Conference on*. IEEE, 2012, pp. 900–906.

[55] Z. Wang, L. Kulik, and K. Ramamohanarao, "Proactive traffic merging strategies for sensor-enabled cars," in *Proceedings of the fourth ACM international workshop on Vehicular ad hoc networks*. ACM, 2007, pp. 39–48.

[56] U. Franke, D. Gavrila, S. Gorzig, F. Lindner, F. Puetzold, and C. Wohler, "Autonomous driving goes downtown," *IEEE Intelligent Systems and Their Applications*, vol. 13, no. 6, pp. 40–48, 1998.

[57] K. J. Malakorn and B. Park, "Assessment of mobility, energy, and environment impacts of intellidrive-based cooperative adaptive cruise control and intelligent traffic signal control," in *Sustainable Systems and Technology (ISSST), 2010 IEEE International Symposium on*. IEEE, 2010, pp. 1–6.

[58] B. Asadi and A. Vahidi, "Predictive cruise control: Utilizing upcoming traffic signal information for improving fuel economy and reducing trip time," *IEEE transactions on control systems technology*, vol. 19, no. 3, pp. 707–714, 2011.

[59] V. Milanés, J. Pérez, E. Onieva, and C. González, "Controller for urban intersections based on wireless communications and fuzzy logic," *IEEE Transactions on Intelligent Transportation Systems*, vol. 11, no. 1, pp. 243–248, 2010.

[60] J. Lee and B. Park, "Development and evaluation of a cooperative vehicle intersection control algorithm under the connected vehicles environment," *IEEE Transactions on Intelligent Transportation Systems*, vol. 13, no. 1, pp. 81–90, 2012.

[61] D. Husch and J. Albeck, "Trafficware synchro 6 user guide," *TrafficWare, Albany, California*, vol. 11, 2004.

[62] J. Harding, G. Powell, R. Yoon, J. Fikentscher, C. Doyle, D. Sade, M. Lukuc, J. Simons, and J. Wang, "Vehicle-to-vehicle communications: Readiness of V2V technology for application," Tech. Rep., 2014.

[63] S. Tuohy, M. Glavin, C. Hughes, E. Jones, M. Trivedi, and L. Kilmartin, "Intra-vehicle networks: A review," *IEEE Trans. on ITS*, vol. 16, no. 2, 2015.

[64] K. M. Strohm, H.-L. Bloecher, R. Schneider, and J. Wenger, "Development of future short range radar technology," in *Proc. of EURAD*, 2005.

[65] C. Blanc, R. Aufrere, L. Malaterre, J. Gallice, and J. Alizon, "Obstacle detection and tracking by millimeter wave radar," *IAV*, 2004.

[66] S. J. Park, T. Y. Kim, S. M. Kang, and K. H. Koo, "A novel signal processing technique for vehicle detection radar," in *Proc. of MTTS*, vol. 1, 2003.

[67] C. Tzomakas and W. von Seelen, "Vehicle detection in traffic scenes using shadows," in *Ir-Ini, Institut fur Nueroinformatik, Ruhr-Universitat*, 1998.

[68] M. B. Van Leeuwen and F. C. Groen, "Vehicle detection with a mobile camera: spotting midrange, distant, and passing cars," *IEEE RAM*, vol. 12, no. 1, 2005.

[69] S.-S. Ieng, J. Vrignon, D. Gruyer, and D. Aubert, "A new multi-lanes detection using multi-camera for robust vehicle location," in *Proc. of IVS*, 2005.

[70] W.-K. For, K. Leman, H.-L. Eng, B.-F. Chew, and K.-W. Wan, "A multi-camera collaboration framework for real-time vehicle detection and license plate recognition on highways," in *Proc. of IVS*, 2008.

[71] P. Chang, D. Hirvonen, T. Camus, and B. Southall, "Stereo-based object detection, classi? cation, and quantitative evaluation with automotive applications," in *Proc. of CVPRW*, 2005.

[72] H. T. Niknejad, S. Mita, D. McAllester, and T. Naito, "Vision-based vehicle detection for nighttime with discriminately trained mixture of weighted deformable part models," in *Proc. of ITSC*, 2011.

[73] J. Kim, S. Hong, J. Baek, E. Kim, and H. Lee, "Autonomous vehicle detection system using visible and infrared camera," in *Proc. of ICCAS*, 2012.

[74] N. A. Mandellos, I. Keramitsoglou, and C. T. Kiranoudis, "A background subtraction algorithm for detecting and tracking vehicles," *ESA*, vol. 38, no. 3, 2011.

[75] D. R. Magee, "Tracking multiple vehicles using foreground, background and motion models," *IVC*, vol. 22, no. 2, 2004.

[76] C. P. Papageorgiou, "A trainable system for object detection in images and video sequences," 2000.

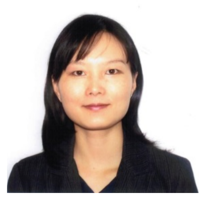
[77] C.-C. R. Wang and J.-J. J. Lien, "Automatic vehicle detection using local featuresa statistical approach," *IEEE Trans. on ITS*, vol. 9, no. 1.

[78] W. Zhang, Q. J. Wu, and H. bing Yin, "Moving vehicles detection based on adaptive motion histogram," *DSP*, vol. 20, no. 3, 2010.

[79] L. Vasu, "Effective step to real-time implementation of accident detection system using image processing," Ph.D. dissertation, Oklahoma State University, 2010.
[80] D. A. Thornton, K. Redmill, and B. Coifman, "Automated parking surveys from a lidar equipped vehicle," *TRPC: ET*, vol. 39, 2014.
[81] R. Sen, P. Siriah, and B. Raman, "Roadsoundsense: Acoustic sensing based road congestion monitoring in developing regions," in *Proc. of SECON*, 2011.
[82] M. Mizumachi, A. Kaminuma, N. Ono, and S. Ando, "Robust sensing of approaching vehicles relying on acoustic cues," *Sensors*, vol. 14, no. 6, 2014.
[83] FCC, "Amendment of the commission's rules regarding dedicated short-range communication services in the 5.850-5.925 ghz band (5.9 ghz band)," Washington, D.C. 20554, Tech. Rep. FCC-02-302A1, 2002. [Online]. Available: https://apps.fcc.gov/edocs_public/attachmatch/FCC-02-302A1.pdf
[84] C. Campolo and A. Molinaro, "Multichannel communications in vehicular ad hoc networks: a survey," *IEEE CM*, vol. 51, no. 5, May 2013.
[85] Y. J. Li, "An overview of the dsrc/wave technology," in *Proc. of HNQRSR*, 2010.
[86] R. F. Atallah, M. J. Khabbaz, and C. M. Assi, "Vehicular networking: A survey on spectrum access technologies and persisting challenges," *VC*, vol. 2, no. 3, 2015.
[87] IEEE, "802.11p: Wireless access in vehicular environments," Tech. Rep., 2010. [Online]. Available: https://www.ietf.org/mail-archive/web/its/current/pdfqf992dHy9x.pdf
[88] ——, "Ieee 1609 - family of standards for wireless access in vehicular environments (wave)," Tech. Rep., 2009. [Online]. Available: https://www.standards.its.dot.gov/factsheets/factsheet/80
[89] D. Allis and R. T. Pack, "Remote vehicle control system and method," 2015, uS Patent 8,954,194.
[90] "Dedicated short range communication," 2016, http://www.its.dot.gov/DSRC/dsrc_faq.htm.
[91] "CAR 2 CAR communication consortium manifesto," 2016, https://www.car-2-car.org/index.php?id=31.
[92] T. Tielert, M. Killat, H. Hartenstein, R. Luz, S. Hausberger, and T. Benz, "The impact of traffic-light-to-vehicle communication on fuel consumption and emissions," in *Proc. of IOT*, 2010.
[93] M. Whaiduzzaman, M. Sookhak, A. Gani, and R. Buyya, "A survey on vehicular cloud computing," *Journal of NCA*, vol. 40, 2014.
[94] "Connected car," 2016, https://www.att.com/shop/wireless/connected-car.html.
[95] A. Ahizoune, A. Hafid, and R. Ben Ali, "A contention-free broadcast protocol for periodic safety messages in vehicular Ad-hoc networks," in *Proc. of LCN*, 2010.
[96] M. S. Almalag, S. Olariu, and M. C. Weigle, "TDMA cluster-based MAC for VANETs (TC-MAC)," in *Proc. of WoWMoM*, 2012.
[97] D. B. Rawat, D. C. Popescu, G. Yan, and S. Olariu, "Enhancing VANET performance by joint adaptation of transmission power and contention window size," *IEEE Trans. on PDS*, vol. 22, no. 9, 2011.
[98] Z. Wang and M. Hassan, "Blind XOR: Low-overhead loss recovery for vehicular safety communications," *IEEE Trans. on VT*, vol. 61, no. 1, 2012.
[99] Y. Park and H. Kim, "Collision control of periodic safety messages with strict messaging frequency requirements," *IEEE Trans. on VT*, vol. 62, no. 2, 2013.
[100] ——, "Application-level frequency control of periodic safety messages in the IEEE WAVE," *IEEE Trans. on VT*, vol. 61, no. 4, 2012.
[101] M. Sepulcre, J. Mittag, P. Santi, H. Hartenstein, and J. Gozalvez, "Congestion and awareness control in cooperative vehicular systems," *Proc. of the IEEE*, vol. 99, no. 7, 2011.
[102] R. Stanica, E. Chaput, and A.-L. Beylot, "Local density estimation for contention window adaptation in vehicular networks," in *Proc. of PIMRC*, 2011.
[103] G. Bansal, J. B. Kenney, and C. E. Rohrs, "LIMERIC: A linear adaptive message rate algorithm for dsrc congestion control," *IEEE Trans. on VT*, vol. 62, no. 9, 2013.
[104] M. Segata, B. Bloessl, S. Joerer, C. Sommer, M. Gerla, R. Cigno, and F. Dressler, "Towards inter-vehicle communication strategies for platooning support," in *Proc. of CTV*, 2014.
[105] M. Amoozadeh, H. Deng, C.-N. Chuah, H. M. Zhang, and D. Ghosal, "Platoon management with cooperative adaptive cruise control enabled by VANET," *Journal on VC*, vol. 2, no. 2, 2015.
[106] P. Fernandes and U. Nunes, "Platooning with IVC-enabled autonomous vehicles: Strategies to mitigate communication delays, improve safety and traffic flow," *IEEE Trans. on ITS*, vol. 13, no. 1, 2012.
[107] M. Jonsson, K. Kunert, and A. Böhm, "Increased communication reliability for delay-sensitive platooning applications on top of ieee 802.11p," in *Proc. of CTV*, 2013.
[108] C. Shao, S. Leng, Y. Zhang, A. Vinel, and M. Jonsson, "Performance analysis of connectivity probability and connectivity-aware MAC protocol design for platoon-based VANETs," *IEEE Trans. on VT*, 2015.
[109] S.-I. Sou and O. K. Tonguz, "Enhancing VANET connectivity through roadside units on highways," *IEEE Trans. on VT*, vol. 60, no. 8, 2011.
[110] A. Abdrabou and W. Zhuang, "Probabilistic delay control and road side unit placement for vehicular ad hoc networks with disrupted connectivity," *IEEE Journal on SAC*, vol. 29, no. 1, 2011.
[111] W. Zhang, Y. Chen, Y. Yang, X. Wang, Y. Zhang, X. Hong, and G. Mao, "Multi-hop connectivity probability in infrastructure-based vehicular networks," *IEEE Journal on SAC*, vol. 30, no. 4, 2012.
[112] C. Han, M. Dianati, R. Tafazolli, R. Kernchen, and X. Shen, "Analytical study of the IEEE 802.11p MAC sublayer in vehicular networks," *IEEE Trans. on ITS*, vol. 13, no. 2, 2012.
[113] D. Jia, R. Zhang, K. Lu, J. Wang, Z. Bi, and J. Lei, "Improving the uplink performance of drive-thru internet via platoon-based cooperative retransmission," *IEEE Trans. on VT*, vol. 63, no. 9, 2014.
[114] Y. Bi, L. X. Cai, X. S. Shen, and H. Zhao, "Medium access control for QoS provisioning in vehicle-to-infrastructure communication networks," *MNA*, vol. 18, no. 2, 2013.
[115] J. Zhao, T. Arnold, Y. Zhang, and G. Cao, "Extending drive-thru data access by vehicle-to-vehicle relay," in *Proc. of VIN*, 2008.
[116] C. Shao, S. Leng, Y. Zhang, A. Vinel, and M. Jonsson, "Analysis of connectivity probability in platoon-based vehicular ad hoc networks," in *Proc. of IWCMC*, 2014.
[117] E. Lee, E.-K. Lee, M. Gerla, and S. Y. Oh, "Vehicular cloud networking: architecture and design principles," *IEEE CM*, vol. 52, no. 2, 2014.
[118] R. Yu, Y. Zhang, S. Gjessing, W. Xia, and K. Yang, "Toward cloud-based vehicular networks with efficient resource management," *IEEE Network*, vol. 27, no. 5, 2013.
[119] M. Gerla, E.-K. Lee, G. Pau, and U. Lee, "Internet of vehicles: From intelligent grid to autonomous cars and vehicular clouds," in *Proc. WF-IoT*, 2014.
[120] N. Lourenço, D. Terra, N. Kumar, L. N. Alves, and R. L. Aguiar, "Visible light communication system for outdoor applications," in *Proc. of CSNDSP*, 2012.
[121] R. Scopigno, A. Autolitano, T. Acarman, Ç. Yaman, and S. Topsu, "The potential benefits of on-board li-fi for the cooperation among vehicles," in *Proc. of ICTON*, 2015.
[122] M. Y. Abualhoul, M. Marouf, O. Shagdar, and F. Nashashibi, "Platooning control using visible light communications: A feasibility study," in *Proc. of ITSC*, 2013.
[123] H. Shin, S.-B. Park, D. Jung, Y. Lee, S. Song, and J. Park, "Vlc transceiver design for short-range wireless data interfaces," in *Proc. of ICTC*, 2011.
[124] B. Tomaš, H.-M. Tsai, and M. Boban, "Simulating vehicular visible light communication: Physical radio and mac modeling," in *Proc. of VNC*, 2014.
[125] "Study on lte support for v2x services," 2015, www.3gpp.org/DynaReport/22885.htm.
[126] M. Blanco, J. Atwood, H. M. Vasquez, T. E. Trimble, V. L. Fitchett, J. Radlbeck, G. M. Fitch, S. M. Russell, C. A. Green, B. Cullinane *et al.*, "Human factors evaluation of level 2 and level 3 automated driving concepts," Tech. Rep., 2015.
[127] P. T. Martens, F. D. Schieben, and J. I. Merat, "Human factors aspects in automated and semi-automatic transport systems: State of the art," 2008.
[128] M. Rahman, M. Chowdhury, K. Dey, R. Islam, , and T. Khan, "Evaluation of driver car-following behavior models for cooperative adaptive cruise control system," *TRR: JTRB*, 2017.
[129] M. Brackstone and M. McDonald, "Car-following: a historical review," *TRF: TPB*, vol. 2, no. 4, 1999.
[130] W. Helly, "Simulation of bottlenecks in single-lane traffic flow," 1900.
[131] S. Panwai and H. Dia, "Development and evaluation of a reactive agent-based car following model," in *Proc. of IVRI*, 2005.
[132] S. Kikuchi and P. Chakroborty, "Car-following model based on fuzzy inference system," *TRR*, 1992.
[133] H. Gong, H. Liu, and B.-H. Wang, "An asymmetric full velocity difference car-following model," *Physica A: Statistical Mechanics and its Applications*, vol. 387, no. 11, 2008.
[134] R. Wiedemann, "Simulation des strassenverkehrsflusses." 1974.
[135] P. G. Gipps, "A behavioural car-following model for computer simulation," *Transportation Research Part B: Methodological*, vol. 15, no. 2, 1981.

[136] Q. Yang and H. N. Koutsopoulos, "A microscopic traffic simulator for evaluation of dynamic traffic management systems," *TRC: ET*, vol. 4, no. 3, 1996.
[137] M. Treiber, A. Hennecke, and D. Helbing, "Congested traffic states in empirical observations and microscopic simulations," *PRE*, vol. 62, no. 2, 2000.
[138] V. Milanés and S. E. Shladover, "Modeling cooperative and autonomous adaptive cruise control dynamic responses using experimental data," *TRPC: ET*, vol. 48, 2014.
[139] S. Jones, "Cooperative adaptive cruise control: Human factors analysis," Tech. Rep., 2013.
[140] Q. H. Do, H. Tehrani, S. Mita, M. Egawa, K. Muto, and K. Yoneda, "Human drivers based active-passive model for automated lane change," *IEEE ITSM*, vol. 9, no. 1, 2017.
[141] M. Rahman, M. Chowdhury, Y. Xie, and Y. He, "Review of microscopic lane-changing models and future research opportunities," *IEEE Trans. on ITS*, vol. 14, no. 4, 2013.
[142] W. Chee and M. Tomizuka, "Lane change maneuver of automobiles for the intelligent vehicle and highway system (ivhs)," in *Proc. of ACC*, vol. 3, 1994.
[143] C. Hatipolglu, K. Redmill, and U. Ozguner, "Steering and lane change: A working system," in *Proc. of ITSC*, 1997.
[144] C. J. Taylor, J. Košecká, R. Blasi, and J. Malik, "A comparative study of vision-based lateral control strategies for autonomous highway driving," *IJRR*, vol. 18, no. 5, 1999.
[145] T. Keviczky, P. Falcone, F. Borrelli, J. Asgari, and D. Hrovat, "Predictive control approach to autonomous vehicle steering," in *Proc. of ACC*, 2006.
[146] J. E. Naranjo, C. Gonzalez, R. Garcia, and T. De Pedro, "Lane-change fuzzy control in autonomous vehicles for the overtaking maneuver," *IEEE Trans. on ITS*, vol. 9, no. 3, 2008.
[147] J. Levinson and S. Thrun, "Robust vehicle localization in urban environments using probabilistic maps," in *Proc. of ICRA*, 2010.
[148] P. G. Gipps, "A model for the structure of lane-changing decisions," *TRB: M*, vol. 20, no. 5, 1986.
[149] A. Best, S. Narang, L. Pasqualin, D. Barber, and D. Manocha, "Autonovi: Autonomous vehicle planning with dynamic maneuvers and traffic constraints," *arXiv preprint arXiv:1703.08561*, 2017.
[150] X. Yang, L. Liu, N. H. Vaidya, and F. Zhao, "A vehicle-to-vehicle communication protocol for cooperative collision warning," in *Proc. of MOBIQUITOUS*, 2004.
[151] A. Weinstock, T. Oron-Gilad, and Y. Parmet, "The effect of system aesthetics on trust, cooperation, satisfaction and annoyance in an imperfect automated system," *Work*, vol. 41, 2012.
[152] M. N. Lees and J. D. Lee, "The influence of distraction and driving context on driver response to imperfect collision warning systems," *Ergonomics*, vol. 50, no. 8, 2007.
[153] J. D. Lee and B. D. Seppelt, "Human factors in automation design," in *SHA*, 2009.
[154] B. D. Seppelt, "Supporting operator reliance on automation through continuous feedback," 2009.
[155] M. S. Carlson, J. L. Drury, M. Desai, H. Kwak, and H. A. Yanco, "Identifying factors that influence trust in automated cars and medical diagnosis systems," in *Proc. of SSS*, 2014.
[156] M. Cunningham and M. Regan, "Autonomous vehicles: human factors issues and future research," in *Proc. of ARSC*, 2015.
[157] D. S. Baquero, W. A. Rogers, and A. D. Fisk, "Human factors issues relevant to automation design: Insights from research on unihabited autonomous vehicles," 2009.
[158] A. Toffetti, E. Wilschut, M. Martens, A. Schieben, A. Rambaldini, N. Merat, and F. Flemisch, "Citymobil: Human factor issues regarding highly automated vehicles on elane," *TRR: JTRB*, no. 2110, 2009.
[159] A. F. Larsson, "Issues in reclaiming control from advanced driver assistance systems," in *Proc. of ECHCDITS*, vol. 2, 2010.
[160] ——, "Driver usage and understanding of adaptive cruise control," *AE*, vol. 43, no. 3, 2012.
[161] T. Fong, C. Thorpe, and C. Baur, "Advanced interfaces for vehicle teleoperation: Collaborative control, sensor fusion displays, and remote driving tools," *AR*, vol. 11, no. 1, 2001.
[162] R. Parasuraman, R. Molloy, and I. L. Singh, "Performance consequences of automation-induced'complacency'," *IJAP*, vol. 3, no. 1, 1993.
[163] M. R. Endsley, "Toward a theory of situation awareness in dynamic systems," *HF: JHFES*, vol. 37, no. 1, 1995.
[164] M. Cummings and J. Ryan, "Shared authority concerns in automated driving applications," 2014.
[165] M. Martens and A. P. van den Beukel, "The road to automated driving: Dual mode and human factors considerations," in *Proc. of ITSC*, 2013.
[166] J. Bredereke and A. Lankenau, "A rigorous view of mode confusion," in *Proc. of CSRS*, 2002.
[167] S. Duffy and J. P. Hopkins, "Sit, stay, drive: The future of autonomous car liability," 2013.
[168] W. Specks, K. Matheus, R. Morich, I. Paulus, C. Menig, A. Lübke, B. Rech, and V. Audi, "Car-to-car communication–market introduction and success factors," in *Proc. 5th European Congress and Exhibition on Intelligent Transport Systems and Services*, 2005.
[169] M. Kuderer, S. Gulati, and W. Burgard, "Learning driving styles for autonomous vehicles from demonstration," in *Proc. of ICRA*, 2015.
[170] "Federal automated vehicles policy," 2016, https://one.nhtsa.gov/nhtsa/av/pdf/Federal_Automated_Vehicles_Policy.pdf.
[171] K. Young, S. Koppel, and J. L. Charlton, "Toward best practice in human machine interface design for older drivers: a review of current design guidelines," *AAP*, 2016.

Ankur Sarker (S'13) received received the BS and MS degree in Computer Science and Engineering from the University of Dhaka, Bangladesh in 2011 and 2014, respectively. He is currently a Ph.D. student in the Department of Computer Science at University of Virginia. His research interests include Cyber-Physical Systems and Wireless Networks, with an emphasis on Data-driven Intelligent Transportation Systems and Mobile Opportunistic Networks. He is a student member of IEEE.



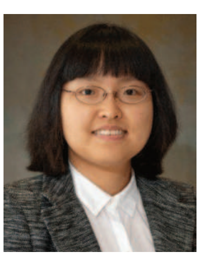
Haiying Shen (SM'13) received the BS degree in Computer Science and Engineering from Tongji University, China in 2000, and the MS and Ph.D. degrees in Computer Engineering from Wayne State University in 2004 and 2006, respectively. She is currently an Associate Professor in the Department of Computer Science at University of Virginia. Her research interests include distributed computer systems and computer networks, with an emphasis on P2P and content delivery networks, mobile computing, wireless sensor networks, and cloud computing. She is a Microsoft Faculty Fellow of 2010, a senior member of the IEEE and a member of the ACM.

Mizanur Rahman (S'12) received the M.Sc. degree in civil engineering from Clemson University, Clemson, SC, USA, in 2013. He is currently working toward the Ph.D. degree in transportation systems engineering with Clemson University. Since 2011, he has been a Research Assistant with Clemson University, focusing on data science and artificial intelligence applications for connected and automated vehicle systems.

Mashrur Chowdhury (SM'12) received the Ph.D. degree in civil engineering from the University of Virginia, USA in 1995. Prior to entering academia in August 2000, he was a Senior ITS Systems Engineer with Iteris Inc. and a Senior Engineer with BellomoMcGee Inc., where he served as a Consultant to many state and local agencies, and the U.S. Department of Transportation on ITS related projects. He is the Eugene Douglas Mays Professor of Transportation with the Glenn Department of Civil Engineering, Clemson University, SC, USA. He is also a Professor of Automotive Engineering and a Professor of Computer Science at Clemson University. He is the Director of the USDOT Center for Connected Multimodal Mobility (a TIER 1 USDOT University Transportation Center). He is Co-Director of the Complex Systems, Data Analytics and Visualization Institute (CSAVI) at Clemson University. Dr. Chowdhury is the Roadway-Traffic Group lead in the Connected Vehicle Technology Consortium at Clemson University. He is also the Director of the Transportation Cyber-Physical Systems Laboratory at Clemson University. Dr. Chowdhury is a Registered Professional Engineer in Ohio, USA. He serves as an Associate Editor for the IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS and Journal of Intelligent Transportation Systems. He is a Fellow of the American Society of Civil Engineers and a Senior Member of IEEE.

Kakan Dey (M'14) received the M.Sc. degree in civil engineering from Wayne State University, Detroit, MI, USA, in 2010 and the Ph.D. degree in civil engineering, with a major in transportation systems, from Clemson University, Clemson, SC, USA, in 2014. He is currently working as an assistant professor with the Department of Civil & Environmental Engineering, West Virginia University, WV, USA. His research interests include heterogeneous communication technology for connected vehicle applications, big data analytics, distributed data infrastructure, and multi-objective analysis.

Fangjian Li received the B.S. degree in vehicle engineering from Hefei University of Technology, Hefei, China, in 2014 and the M.S. degree in automotive engineering from Clemson University, Clemson, SC, USA in 2016. He is currently a Ph.D. student in the Department of Mechanical Engineering, Clemson University. His research interests include controls and human-centered design in intelligent transportation systems.



Yue Wang (M'11) received the B. S. degree from Shanghai University, China, in 2005, and M.S. and Ph.D. degrees from Worcester Polytechnic Institute in 2008 and 2011, respectively. Prior to joining Clemson in 2012, she was a postdoc in the Electrical Engineering Department at the University of Notre Dame. She is currently the Warren H. Owen - Duke Energy Assistant Professor of Engineering at Clemson University. Her research interests include cooperative control and decision-making for human-robot collaboration systems, cyber-physical systems, and multi-agent systems. She was a receipt of the Air Force Young Investigator award in 2016 and NSF CAREER award in 2015. She is the chair of the IEEE CSS TC on Manufacturing Automation and Robotic Control and a member of the IEEE RAS TC on Multi-robot Systems.

Husnu S. Narman received his B.S. degree in Mathematics from Abant Izzet Baysal University, Turkey, in 2006, M.S. degree in Computer Science from University of Texas at San Antonio, San Antonio TX, USA in 2011, and PhD degree in Computer Science from University of Oklahoma, Norman OK, USA, in 2016. Currently, he is a faculty member at Marshall University, Huntington WV, USA. His research interests include queuing theory, network management, network topology, Internet of Things, and Cloud Computing.