A Review of Communication, Driver Characteristics, and Controls Aspects of Cooperative Adaptive Cruise Control (CACC)

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***Abstract*—Cooperative adaptive cruise control (CACC) systems have the potential to increase traffic throughput by allowing smaller headway between vehicles and moving vehicles safely in a platoon at a harmonized speed. CACC systems have been attracting significant attention from both academia and industry since connectivity between vehicles will become mandatory for new vehicles in the USA in the near future. In this paper, we review three basic and important aspects of CACC systems: communications, driver characteristics, and controls to identify the most challenging issues for their real-world deployment. Different routing protocols that support the data communication requirements between vehicles in the CACC platoon are reviewed. Promising and suitable protocols are identified. Driver characteristics related issues, such as how to keep drivers engaged in driving tasks during CACC operations, are discussed. To achieve mass acceptance, the control design needs to depict real-world traffic variability such as communication effects, driver behavior, and traffic composition. Thus, this paper also discusses the issues that existing CACC control modules face when considering close to ideal driving conditions.**

***Index Terms*—Cooperative adaptive cruise control (CACC), communication protocols, driver characteristics, controls, string stability.**

I. Introduction

Surface transportation systems form the backbone of national economic prosperity, which provides reliable transportation of passenger traffic and freight movement for domestic and international trade. However, every year more than 30,000 people die from roadway crashes on US highways [1], and growing traffic demand causes significant congestion on major urban areas and corridors [2]. While driver error has been considered as the leading cause of most crashes [3], limited transportation infrastructure capacity is one of the primary reasons of congestion [2]. To handle these issues, transportation agencies have been implementing non-traditional transportation solutions such as the Intelligent Transportation System (ITS) applications to maximize the efficiency of existing transportation system capacity, and to improve traffic safety [4]–[7].

In particular, the introduction of automation into vehicles [8] and wireless communication in a connected vehicular environment are potentially transformative, which can improve safety and mobility efficiency. They can also reduce environmental impact of transportation system [9]. To facilitate the research and implementation of automation in vehicles, the National Highway Traffic Safety Administration (NHTSA) classified five distinct automation levels; from level 0 (no-automation) to level 4 (full automation) [10]. A similar classification has been defined by the Society of Automotive Engineers (SAE), which outlined six levels: level 0 (no-automation) to level 5 (full automation) [11]. The first automation driving support system, the conventional cruise control (CCC) allows drivers to drive at a certain speed. In recent years, with the improvement of vehicle control technology, the adaptive cruise control (ACC) system allows a vehicle to drive behind a leader at a certain distance, which improves roadway capacity and traffic safety as well as fuel efficiency [8]. This system is designed to further improve the driving experience such as comfort. Enabling the connectivity between vehicles and roadside units, ACC application could be extended to form a platoon known as cooperative adaptive cruise control (CACC) [12] and belongs to NHTSA and SAE defined level 2 automation. With the shared information between vehicles, the CACC allow vehicles in a platoon to maintain smaller headway compared to ACC [13]. The Partners for Advanced Transit and Highways (PATH) program in California has been involved in the research of connected and autonomous vehicles for over 30 years. They have conducted CACC system control and stability study as well as real-world experiments [14].

With a 100 percent penetration level of CACC in the traffic stream, traffic throughput could reach more than 4,200 veh/hr/ln

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[15], while the maximum throughput in manual driving conditions is around 2,000 veh/hr/ln [16]. Park *et al.* showed in a simulated signalized corridor that CACC can reduce emission and fuel consumption by more than one-third [17]. Furthermore, one of the major causes of crashes is the heterogeneous driving behavior in traffic stream and the human errors. The CACC application will reduce this diversity by forming a platoon with small space/time headway [12]. There are numerous studies that explore the feasibility of CACC in simulation and real-world highway systems [15], [18], [19]. The fundamental building blocks of CACC operations can be classified into three primary challenges:

1) Communication between vehicles and roadside units must establish the connectivity between vehicles to exchange real-time vehicle position, velocity, and acceleration data to support maintaining certain following distance between them;
2) CACC interfaces for drivers must address how a driver will interact with the CACC system depending on driving conditions and CACC system generated instructions; and
3) Control strategies in vehicles must deal with how communication between vehicles can be integrated to obtain appropriate actions to maintain safe CACC operations as well as control actions in case of CACC system failure or effects of human factors in control design.

In this paper, the authors review literature to compile existing knowledge and issues with communications, driver behaviors and controls related to CACC in Sections II–IV, respectively, with potential future research directions. Concluding remarks are presented in Section V.

II. Communication

Communication is a critical requirement in the implementation of CACC systems. Connected Vehicle Reference Implementation Architecture (CVRIA) developed by US Department of Transportation provides the communication framework between vehicles and roadside units [10], which include vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications [20]. In networks composed of inter-connected vehicles, communication is realized in autonomous manner without central management [20]. Since the communication bandwidth could become insufficient when the number of served vehicles increases inside the coverage area, short-range wireless technologies are more advantageous for vehicular communication [21]. Dedicated Short Range Communications (DSRC) has been chosen as the standard communication protocol for connected vehicle applications. The Federal Communications Commission (FCC) in the US scheduled that DSRC operates on 5.9 GHz with a bandwidth of 75 MHz [22].

Vehicular Mobile Ad Hoc Networks (VANETs) is one of the extensively explored methods for vehicular communication. VANETs distinguish themselves from other Mobile Ad Hoc Networks (MANETs) in various features, such as high node mobility and dynamic topology [23]. Another form of vehicular network is Vehicular Delay Tolerant Network (VDTN), where end-to-end connection doesn't always exist [24]. The major difference between VANET and VDTN is in connection among nodes. VDTNs adopt the store-carry-forward paradigm, which is inherited from Delay Tolerant Networks (DTNs), to support applications without continuous connection. The forwarding of packets is achieved by the movement and contact of vehicles in different regions of the network. Based on VANET and VDTN, various types of connected vehicle applications, ranging from traffic safety and traffic management to entertainment can be developed. When cooperation exists among connected vehicles, their vehicular communication systems enable more effective autonomous control. An example of an autonomous control system in connected vehicles is the CACC system. The V2V communications can help autonomous control systems to determine whether the movement pattern change of the leading vehicle is significant enough for the following vehicles to brake early enough to ensure the minimum gap.

This section discusses existing wireless networking protocols that could be utilized in the CACC operations. Various unicast, multi-cast and broadcast routing protocols are classified and summarized focusing on their applicability and drawback for CACC systems. A summary on suitability of the existing communication protocols for CACC is presented at the end of the section.

A. *Routing Protocols for VANETs*

This section reviews previous VANETs' protocols from the perspective of their suitability for CACC systems. Derived from the traditional routing protocols for MANETs, e.g., Dynamic sources Routing (DSR) [25] and Ad-hoc On Demand distance Vector routing (AODV) [26], several routing protocols for vehicular communication networks have been proposed. Because of the distinct characteristics of VANETs (e.g., high vehicle mobility, dynamically changing topology), these traditional topology based routing protocols are no longer efficient. Thus, through combining location information with node mobility, several routing protocols were proposed, all of which considered the unique characteristics of moving vehicles. Several major representative algorithms are presented in Table I.

In summary, existing routi7ng protocols for VANETs have explored various aspects on utilizing roadway characteristics or relays to achieve acceptable performance but still have problems on specific application for CACC, such as lack of methods against high mobility, low disruption tolerance, large delay, etc.

B. *Routing Protocols for VDTNs*

The routing protocols for VANETs simply assume that stable and reliable V2V or V2I connection exists in vehicular networks. However, vehicle networks usually suffer from frequent disconnection and partitioning, so the fundamental assumption of majority of VANET protocols does not always hold true. Thus, the store-carry-and-forward routing approach of DTN is introduced in vehicle networks. Different from traditional DTNs, the routing of VDTNs assumes a layered architecture that packages large data packets into *bundles* [35]. As the future CACC systems may face situations with large delays and an occasionally-connected network, we present existing

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TABLE I
REPRESENTATIVE VANET ROUTING ALGORITHMS AND SUITABILITY FOR CACC

Algorithm	Properties	Delay	Suitability for CACC	Communication Protocol
Greedy Perimeter Stateless Routing (GPSR) [27]	Nodes keep the location information of their first hop neighbors. By forwarding the packet to the nearest node to the packet destination, the packets are delivered in a greedy manner. If forwarding holes are encountered, which means no qualified neighbors can be found, it changes to perimeter mode to overcome local maxima situation (perimeter forward).	Medium	Suitable for CACC system with a large number of vehicles	802.11 Wave LAN radios
Intersection-based Geographical Routing Protocol (IGRP) [28]	IGRP uses roadside units (RSUs) to reach the Internet. Through formulating an optimization problem, the network connectivity probability among successive RSUs can be maximized with QoS requirements satisfied under various conditions.	Low	Suitable for CACC	
Hybrid Location based Ad-Hoc Routing (HLAR) [29]	HLAR discovers route by using overall available location information. If location information is unavailable or limited, HLAR is switched to on-demand routing. The simulation results showed that HLAR excels in reducing overhead and improving scalability compared to previous on-demand routing protocols. However, the best reliable route is not guaranteed since a reverse link to the source is not always provided.	Medium	Not directly suitable for CACC, but could be combined with multiple algorithms to adapt to various situations	802.11b
Junction-based Adaptive Reactive Routing (JARR) [30]	In JARR, packets are forwarded between junctions. JARR lets each node use a beacon to inform neighboring nodes of its position and velocity. Based on the estimated node density on all paths, JARR finds the fastest path and direction to the expected positions. However, since each distance between junctions must be pre-calculated and stored in nodes, JARR is not scalable.	Medium	Suitable for CACC with delay tolerance requirement	802.11
PROMPT [31]	PROMPT is designed for V2I communications in urban environment assisted with positional services. To handle network sparsity issues, the PROMPT packets without suitable forwarding vehicles will be held by their current carrier until the right time comes. As for path routing, it exploits digital roadmaps with positional information.	Low	Suitable for CACC with RSUs	DSRC
Back-Bone-Assisted Hop Greedy (BAHG) [32]	BAHG aims at discovering routing path with minimum relay cost. It introduces a group of nodes, which operate as connection point at intersections, as backbone nodes. More over, with the tracked positions of source and destination, the forwarding of packets can be realized with dynamic directions.	Low	Suitable for CACC	802.11b
Vehicle-Assisted Data Delivery (VADD) [33]	It utilizes the relation between packet delivery delay and vehicle density. Each roadway is depicted with a link of which vehicle driving speed is subject to its vehicle density. The delivery direction is determined at each junction where the packet is persistently forwarded along the path with the minimum delay. To realize this, VADD nodes have the knowledge of their positions and traffic statistics on the roads.	Low	Suitable for CACC with high vehicle density	802.11
Static Node-assisted Adaptive Data Dissemination Protocol (SADV) [34]	Low vehicle density may prevent the discovery of continuous packet delivery paths. To solve this problem, SADV packets will wait for their optimal paths at intersections. Each intersection will be attached with a RSU which can carry the packet when the optimal path is found.	Medium	Suitable for CACC with RSUs	802.11

routing protocols designed for unicast, multicast and broadcast in VDTNs, and also review approaches for congestion control and traffic differentiation during routing. Our major focus is discussing their applicability value on the CACC systems.

1) Unicast Protocols: Unicast routing protocols consist of single-copy and multi-copy forwarding protocols. The single-copy forwarding protocols have one unique bundle in the network throughout the forwarding process. The multiple-copy protocols replicate bundles during vehicle contact to improve the success rate of delivery. On the other hand, these unicast routing protocols decide which node or nodes are needed to forward the bundles based on different strategies and knowledge about the network. For communications in CACC systems, the leading vehicle may need to establish a unicast routing path to the following vehicles. In this section, we classify the routing protocols based on their different forwarding approaches, identify whether a routing protocol uses single- or multi-copy forwarding and discuss their applicability for CACC.

Geographic-based forwarding: Geographic-based routing is a promising packet forwarding principle for VDTNs, which relies on geographic position information extracted from navigation systems that have been widely used nowadays. Geographical Opportunistic Routing for Vehicular Networks (GeOpps) schedules the route from vehicles' starting position to their requested destinations based on the positional information provided by navigation systems, which include GPS devices, maps and functions [36]. Thus, the vehicle that is approaching the final destination of a bundle is selected as its next bundle carrier. One basic assumption in GeOpps is that a vehicle having a shorter estimated arrival time to destination can always be found nearby. During the delivery of packets, the arrival time of each vehicle is calculated, the packet will always carried by the vehicle with the shortest arrival time.

Since GeOpps is limited to single-copy routing, the packet forwarding path is not optimal. GeoSpray was proposed as a combination of VDTN relay technique and path scheduling

[37]. Multi-copy routing schemes provide alternate paths for choosing, while single-copy routing consumes much less resource. To reduce the number of duplicated copies with increased efficiency, GeoSpray uses a hybrid version of the Spray and Wait protocol to adaptively control the number of bundle copies [38]. Initially, it utilizes multi-copy scheme, which aims at finding an optimal path by spreading several bundle copies. Afterwards, it utilizes single-copy scheme to efficiently deliver packets with limited overhead. To eliminate duplicate bundles caused by multi-copy scheme, GeoSpray introduces the *active receipts*. Simulation results demonstrate that GeoSpray has improved delivery success rate, delivery delay but increased overhead compared with GeOpps. Compared with other multi-copy routing protocols, such as the Spray and Wait [38] and the Epidemic protocol [39], its duplication overhead is acceptable.

One limitation of these geographic routing works is that they fail to consider the mobility of destination nodes or assume that the destination is a static place. To this end, Kuiper *et al.* proposed a geographic routing protocol called Location Aware Routing for Delay-Tolerant Networks (LAROD), which uses a Location Dissemination Service (LoDiS) to disseminate data in intermittently connected VANETs [40]. Cao *et al.* proposed Converge And Diverge (CAD) [41], which utilizes utility replication for routing [42]. It firstly estimates the movement range of destination, and then uses a two-phase routing scheme to relay bundles to the destination. CAD is the improved version of Come-Stop-Leave (CSL) approach [43]. CSL focuses on reducing the number of replications towards fixed destinations using geographic information, while CAD focuses on replicating packets to mobile destinations through estimating their movement range from historical records of location, speed and travel time.

Sidera *et al.* proposed Delay Tolerant Firework Routing (DTFR), which is another hybrid delegation forwarding protocol utilizing geographical information [42], [44]. DTFR forwards messages to the destination in greedy manner. It combines phases similar to Spray and Wait protocol [38] and greedy packet forwarding in DTNs. Firstly, instead of the target destination, the bundles are forwarded to a position, namely the firework center, in single-copy manner. Once a path to the actual destination is found, the message will be forwarded using the path. Since DTFR is a hybrid protocol using both single-copy and multi-copy schemes, it has lower overhead compared with CAD.

A hybrid geographic based algorithm, Geographic and DTN routing with navigation assistance (GeoDTN+Nav) [45], is proposed to deal with the heterogeneity of vehicle distribution. It has multiple modes for different scenarios. The situation to switch between different modes is determined by the partition status of the network. For example, when vehicle density is high, it uses greedy mode, but if the vehicle density becomes sparse, it switches to DTN mode. The forwarding method combines the DTN mode with the perimeter mode to traverse the obstacle or voids [27]. The decision of switching between different modes is based on the length of the forwarding path and its delivery quality.

From the above approaches, it can be seen that geographical information is useful in assisting communications among vehicles. Though combining geographical information with real-time message exchange techniques, CACC has less communication range constraints, such as ignorance of road geometry and complete information of destination.

Mobility prediction based forwarding: Trajectories recommended by navigation devices provide useful prediction of node mobility in the future. By scheduling routing path according to the trajectory information, the optimal route to forward packet can be found. Wu *et al.* discovered a spatial-temporal correlation in vehicle mobility based on current vehicle position and historical trajectory information. They noted that the correlation between a vehicle's past trajectory and future movement can be used for improving packet delivery [46]. Nonetheless, such prediction is not feasible for VDTNs, which have dynamic topology and intermittent connection, especially for CACC application scenarios which require accurate information of vehicle's movement.

In vector based routing, the node movement is represented with a vector generated from vehicles' change of movement angle, position and velocity [47]. The vector means vehicles' velocity and direction of movement. To accelerate the replication process, the bundles are carried by neighbors departing from the source. Bundles will not be replicated to the neighboring vehicles moving along the same route, because such a vehicle is quite likely to meet the nodes that the carrier node has just passed through. The major drawback of this routing is that the memory overhead on static nodes will be high because every other moving node is moving away from them. Similarly, instead of considering multiple directions, Schwartz *et al.* proposed a data dissemination protocol considering only forward and backward directions, and whether the vehicle is at the tail or the non-tail position of a cluster [48].

In History based Vector Routing (HVR) [49], which extends from the vector based routing [47], each node remembers its encounter history and its own locations. Upon meeting, nodes send each encounter node their vector information. They also maintain a database recording the location of all their neighboring nodes, which can be used for deducing encounter position for certain bundles.

Based on actual records of inter-contact times among vehicles, which are extracted from two metropolitan cities of China, Zhu *et al.* proposed an approach to schedule packet forwarding among vehicles [50]. By establishing higher order chains to predict the time interval between the neighboring contacts of two vehicles, a greedy forwarding protocol is designed for making routing decisions. Compared with other two representative algorithms, [51] and [52], the Markov chain based method achieves lower delivery delay and higher delivery success rate.

In majority of works, the encounters between nodes are utilized without fully considering the characteristics of the contact, such as temporal and spatial characteristic. To make up this defect, Predict and Relay (PER) [53] is proposed based on two observations. First, instead of random movement, which is commonly assumed in many works, nodes have skewed preference in moving around a certain set of popular landmarks. Second, node movement history is helpful in extracting the above preference. PER employs a time-homogeneous semi-Markov chains for predicting node contact probabilities. The final utility metric for destination is calculated by the transition matrix and the sojourn time probability distribution matrix. Similarly, REgioN bAsed (RENA) takes into account various parameters of nodes (e.g., staying time, encounter time, return time) in locating the packet destination [54]. Such information is extracted from the historical regional movement of nodes.

In summary, as a vehicle's movement is relatively constrained in several states and highly relevant with neighboring vehicles' state, VDTN algorithms focusing on utilizing or developing more sophisticated mobility prediction schemes will help the CACC system achieve better communication performance. For example, with the knowledge of routes that vehicles most frequently follow, CACC system will more easily schedule connection among vehicles.

Incentive-based cooperative forwarding: CACC requires vehicles to fully share their current moving states. However, most of the previous forwarding algorithms require participating nodes to be cooperative and keep forwarding bundles without bias, which provides no guarantee for practical situations because most users will be selfish. As illustrated in [55], [39] and [57], participating nodes tend to be selfish and their selfishness will impair the performance of packet forwarding since rational participants would like to save resources rather than actively share information with others.

Based on the difference in motivation methods, we have the following classification for existing incentive based approaches [58]. The *first* category includes exchange based systems that aim at letting nodes benefit each other through cooperation. Such systems are easy to implement because each exchange process is improvised. However, the exchange based approach can easily fail due to asynchronous service and corresponding reward or due to ignorance of whether the other nodes have provided service to that node. The *second* category uses virtual currency as the credit for encouraging nodes to cooperate as designed. These approaches require large investment in billing infrastructure and centralized management of the records. The *third* category majorly consists of reputation-based approaches that quantify the services nodes offered and received. Such methods suffer from the same drawbacks of the credit-based methods.

Tit-For-Tat (TFT) strategy [57] is a credit-based algorithm which pays credit to nodes according to their contribution in relaying bundles. The method uses a pair-wise TFT strategy to constrain the behavior of selfish nodes. However, to make the credit based schemes operable, security mechanisms are needed. To this end, based on a multi-layer structure consisting of a base layer and several endorsement layers added by the intermediary nodes offering forwarding services, a Social MAp based RouTing (SMART) algorithm is proposed [59]. Additionally, to resist possible attacks, SMART incorporates several security measures.

The Practical incentive (Pi) focuses on fairness with more detail [56]. In Pi, the payment of credit is centrally managed by the source exclusively when the assisted bundles have arrived at the expected destination. To motivate node participation, the intermediate nodes can still earn certain credit if the final forwarding of the bundle fails. In [60], a game theoretical approach is proposed which determines the payoff allocation for cooperating nodes based on coalitional game theory.

Li *et al.* claimed that the performance of traditional epidemic routing will be impacted by node's selfish behaviors [39]. Such claim is verified by directly using Markov processes when the network has two communities. Through modeling the message delivery process with a 2D Continuous Time Markov Chain, the delivery delay and the delay cost are represented with state transitions explicitly. Li *et al.* further studied the impact mechanism of nodes' social selfish behavior on multicasting [55]. However, the methods proposed in [39] and [55] are incapable in front of the curse of the big state space.

As CACC requires vehicles to share their driving information with others, developing a proper incentive-based rule to encourage vehicles to cooperate is necessary. Specific incentive rules combining CACC requirements with existing efforts are expected.

2) Multicast Protocols: For CACC aiming to disseminate a message to a group of vehicles, such as safety applications and traffic management applications that require communication beyond pairwise communication supported by unicast protocols, multicast communication schemes are needed. For driving safety, the information of roads, which includes intersections, traffic density, road surface condition, accident probability and road blocks, can be fed into vehicles through group communications. Thus, applying multicast schemes in V2V communications is necessary.

Generally, the multicast protocols in VDTNs consist of two types: topology-based approaches and position-based approaches. The former uses network topology for selecting forwarding nodes, while the latter relies on positional information, which includes the source node position, the destination node position, neighboring node position and multicast region coordinates.

In the topology-based approaches, Yi *et al.* presented a mesh-based protocol for VANETs, namely the On-Demand Multicast Routing Protocol (ODMRP) [61]. In each forwarding process, a subset of nodes will be responsible for sending the multicast packets via scoped flooding. A multicast mesh is created upon the request of sending a multicast source. Another similar multicast protocol is the Multicast Optimized Link State Routing (MOLSR) protocol [62]. However, in MOLSR, source-based multicast trees are set up with an underlying unicast routing protocol. The address determined by the multicast trees is used to forward multicast packets. However, to ensure efficiency, a few packets will be disseminated while the establishment of the multicast tree is still in progress. These packets may suffer from inferior performance, which makes these multicast algorithms unsuitable for safety and emergency applications.

In the position-based approaches, additional location service is needed. The Position Based Multicast (PBM) is a generalized routing on multiple destinations relying on location services [63]. In PBM, a multicast tree is established to determine the multicast group that has the lowest cost. For a V2V network with highly dynamic topology and larger number of multicast recipients, the PBM protocol may not be appropriate. This is because under this case, the highly dynamic mobility of vehicles always impairs the timeliness of vehicle positions. Also, attaching the position information of recipients to the packet header will increase the size of the overall packet, which results in low efficiency of packet utilization and redundant packet processing. Scalable position-based multicast (SPBM) improves the scalability of multicast (namely multicast with controlled recipients,) through hierarchical group management [64]. Based on the geographical characteristic of different regions, a quad tree is used to partition the network into regions with particular combination of predetermined aggregation levels. Also, the group member's location information propagated to upper hierarchy makes SPBM less subject to dynamic node mobility and less frequent flooding to remote regions. Robust and Scalable Geographic Multicast (RSGM) [65] is an extension to SPBM. In contrast, RSGM uses unicast routing for multicasting packets. New VDTN, PRoPHET, combines a geographic routing protocol with Spray and Wait protocols [66]. It tests the performance of protocols in low vehicle density scenario, which correspond to a rural area, and high vehicle density scenario, which correspond to an urban area. The identification of dense and sparse scenarios is accomplished through estimating the number of nodes encountered. In dense scenarios, the messages are assigned TTL by sources. While in spare scenarios, a Weighted Fair Queuing (WFQ) scheduling strategy is used, and the messages are maximally forwarded to vehicles to increase the success rate of delivery.

3) Broadcast Protocol: To fulfill packet delivery in larger vehicular networks, many broadcast protocols have been proposed. For broadcasting in connected vehicles, the packets are disseminated centrally to other destinations. Broadcasting is suitable for vehicular networks not only for its shorter handshake time with other nodes, but also for its resilience of requiring no concrete delivery path. Since broadcast in vehicular networks disregard network topology, movement patterns or traffic patterns, flooding is suitable for broadcasting in groups of vehicles. The reliability of flooding in vehicular networks has been discussed in [67]–[70]. Message broadcasting based on location-based information, such as position and direction [71], interest of position [72], and roadway scheduling [73], have been widely studied.

However, flooding is always too expensive for vehicular networks due to its bandwidth inefficiency, duplicate packets, etc. Thus, the vehicular broadcast protocols usually put limit on the number of participants in data forwarding to ensure scalability. To indicate the drawback of generic ad hoc network solutions for vehicular networks and the necessity of broadcast methods, Sun *et al.* proposed Vector-base TRAcking DEtection (V-TRADE) [74]. In V-TRADE, upon packet forwarding, the neighbors of a vehicle are requested for their locations and driving direction. The relay node is then selected based on the requested information. The delay performance of V-TRADE is inferior to normal broadcast algorithms. Also, the controlled broadcast brings much overhead for applications.

Urban multi-hop broadcast (UMB) proposed by Korkmaz *et al.* provides broadcast service in vehicular networks with suppressed redundancy [68]. UMB only allows the furthest vehicle to rebroadcast the RTS/CTS like packets. In the refined version of UMB, the Ad Hoc multi-hop broadcast (AMB), the repeaters at the intersections are replaced with lightweight RSUs which support directional broadcast [75]. An improved multi-hop vehicular broadcast (MHVB) protocol introduced by Mariyasagayam *et al.* realizes the efficient dissemination of traffic safety related information [76]. It defines a traffic congestion detection algorithm for suppressing unnecessary packet delivery, and a backfire algorithm for efficient forwarding of packets throughout the network. Based on the location of vehicles provided by GPS devices and a map database, the mobility-centric data dissemination algorithm (MDDV) proposed by Wu *et al.* enables vehicles to forward broadcast packets by exploiting vehicle mobility [77]. MDDV lets vehicles move towards the destinations, which are named the message heads, to store and carry the message. Similar to UMB, Fasolo *et al.* proposed the Smart Broadcast (SB) algorithm that uses Request-to-Send (RTS) and Clear-to-Send (CTS) messages to deduce each node's distance relative to the source node [78].

Ros *et al.* proposed a broadcast algorithm with acknowledgment based on a connected dominating set, which can provide high reliability and message efficiency [79]. They developed the Acknowledged Broadcast Strategy (AckBSM) for various scenarios, which range from static to mobile. AckBSM uses the identifiers attached to circulated broadcast beacons to determine whether the retransmission of message is needed. With such a design, the acknowledgement is realized in the store-carry-forward manner.

From the above analysis, it is evident that broadcast is suitable for data dissemination in CACC because fully sharing vehicles' current operation status is the prerequisite of establishing reliable platoon-based cruise control. However, drawbacks of existing broadcasting techniques, such as low delay tolerance, and heavy reliance on position service under mobile environment also limit its application on connected vehicle networks. Therefore, specific broadcast algorithms for vehicular networks need to be explored.

4) Congestion Control and Traffic Differentiation: In vehicular networks, the forwarding of bundles is not continuous and multiple replicas of bundles exist, which can lead to congestion in the networks. Therefore, it is predictable that communications in CACC will be traffic intensive. The usual operation for congested nodes is to drop incoming bundles regardless of their content, which results in deteriorated delivery performance and resource wastage.

One major cause to congested network is the asynchronous knowledge of whether the packet has been successfully delivered. Hence, some nodes may keep storing the successfully delivered bundles due to the absence of acknowledgement. To overcome this drawback, Bindra *et al.* proposed the acknowledgement method to notify the nodes of the status of the bundles [80]. Thus the successfully delivered bundles can be dropped according to the received acknowledgements.

Moreover, Thompson *et al.* used Markov chains to analyze the mechanism of network condition variation [81]. The basic idea of this work is to utilize a drop-replication ratio, which is determined from local network status, to control packet replication. Through combining with acknowledgement approaches, the bundle congestion can be avoided and controlled dynamically.

Soares *et al.* proposed two differential buffer management approaches and corresponding dropping policies to identify

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bundles for applications with different priorities [82]. The evaluation results demonstrate that the forwarding performance of the low and medium priority application bundles is improved, while the delivery of bundles for high class application is greatly deteriorated. Motivated by this work, Shin *et al.* proposed to estimate the priority of messages based on exchange rate and nodes' knowledge [83].

Although congestion control or traffic differentiation is the supplemental technique for communication in CACC, it is worth exploring because the contact environment in vehicular networks is harsh. Thus, the communication technique should be effective and efficient.

C. Challenges and Open Issues in Vehicular Networks

Several major challenges remain in the field of vehicular networks as the support for CACC.

1) Security and Privacy: Black hole and gray hole attacks can cause severe problems in VDTNs. Detection and mitigation of black holes and gray holes represent a significant research area in VDTN [84], [85]. There are a few methods such as Misbehavior Detection System and Encrypted Verification Method (EVM) to detect and remove black holes and gray holes [86]. However, each of these methods is only applicable in a specific traffic model. There is no 'one size fits all' method. Security issues regarding traffic patterns in future CACC systems will be a direction worth exploring. Privacy is a concern in VDTN as intermediate nodes would come to know the location of the sending node. Through an efficient social evaluation scheme, it is possible to make use of trustworthy forwarders in social aware message routing and data dissemination [87], [88]. Technologies need to be developed to realize the above communication schemes while preserving privacy of participants.

2) Social Aware Vehicular Networking: Placing/deploying RSUs in various critical highway locations, such as intersections in cities, could help lessen routing congestion in those areas [88]. Social centrality assessments of highway networks will help in placing RSUs at intersections. For example, considering the weight of road can be measured with their traffic volume, the intersections or road segments carrying the heaviest traffic should be placed with the most RSUs. Based on the unique social relation among vehicles, more social aware vehicular networking techniques are expected in the future.

3) Multicast and Broadcast Routing: Transmission efficiency and throughput are two important parameters that come into the picture when we talk about broadcast and multicast routing in VDTNs. Throughput of the network in these scenarios can drastically improve through rateless codes such as network coding and erasure coding [89]. Instead of plain replication of bundles/packets, these rateless coding techniques provide a new way to generate and replicate bundles/packets. These techniques provide near to optimal solutions asymptotically as the network scales high. However, more sophisticated multicast and broadcast routing techniques are also needed for future CACC systems.

4) Policing and Traffic Differentiation: In vehicular networks, information transmitted is classified into traffic information and entertainment information. Since these networks are disruption prone, it is very important to prioritize information categories in the QoS of these networks [90]. Traditional QoS protocols like DiffServ and IntServ cannot be blindly adopted in these types of networks [90]. NHTSA and VSCC (Vehicle Safety Communications Consortium) provide references for the maximum latency that each kind of packet should experience [21]. However, specific QoS protocol for CACC systems has not been studied yet.

5) Naming and Addressing of VDTN: Conventional naming and addressing schemes do not suit VDTNs. End point identifiers should be addressed based on their locations which could be a combined function of host and region [91]. There are not many techniques available for adaptive address mapping and resolution for vehicular communication under mobile topologies. Therefore, suitable naming and addressing schemes for vehicular networks are necessary.

D. Summary and Future Research

In Section II, we surveyed various data communication protocols for vehicular networks and explored the possible application fields of these techniques in CACC. Firstly, several algorithms for VANETs were presented and their application possibility for sparse vehicular networks was discussed. Then, various data dissemination protocols for VDTNs were presented. The authors categorized the existing publications for VDTNs according to their technical focuses, including information based forwarding, incentive based forwarding and social based forwarding, etc. Subsequently, the authors summarized several possible scenarios regarding the application of CACC and how the vehicular networking techniques can be used to support reliable communications between vehicles in platoon. The future research for CACC routing support will be in the proper scheduling of multiple vehicles or platoons in inter-connected environment or sparsely connected environment from macro perspective, such as, speed suggestion/administration based on real Floating-Car Data (FCD). Additionally, the roadside units (RSUs) infrastructure for CACC operations also brings challenge, such as the access point distribution or the workload assignment of vehicle computing source.

III. Driver Characteristics

Driver characteristics are the complex factors in the development of CACC systems. At the soon-to-come forefront of government initiatives to mandate connectivity in new vehicle models in the US [92], automotive manufacturers and researchers are developing and prototyping vehicle connectivity applications to improve safety (e.g., collision warning) and driving experience (e.g., congestion avoidance). To attain user adoption, the connectivity supported applications and services need to model driver characteristics precisely before real-world deployment in new vehicle models. While the major benefits of enabling CACC are improved traffic flow stability, safety and infrastructure capacity, how drivers will participate and react to the actions of cooperative vehicles is critical. In this section, the authors have compiled the driver behaviors in a CACC environment into the following three different categories:

i) driver acceptance, ii) reduction in workload and distraction, and iii) driver behaviors in traffic streams [93].

A. Driver Acceptance

CACC systems will reduce driving stress, drivers' fatigue, and drivers' judgment errors [93]. Similarly, the introduction of CACC features will provide opportunities for automakers to develop new vehicle models that will add new dimensions to their product line, which will be appealing to a new tech savvy group of users. Enabling CACC to control the longitudinal position of vehicle is challenging and requires performing five distinct tasks—i) perceiving leading vehicle action, ii) interpreting leading vehicle action, iii) deciding to take actions, iv) evaluating available options, and v) executing the response [94]. The first four steps depend on drivers' reaction time, which varies according to the physical and mental state of the drivers [95]. As CACC will reduce driver involvement by reducing typical driver information processing time and by harmonizing the reaction and execution time of the first four tasks, it will improve traffic operational efficiency and capacity significantly. V2V and V2I connectivity enabled by DSRC or other wireless communications will reduce time required to perform first four tasks compared to drivers' longer reaction time.

Though the primary objective of CACC is to maintain a certain gap in a CACC platoon, one critical task is to investigate how collision avoidance systems can be executed when emergency stopping is required with or without driver involvement [91], which is yet to be explored. While recommended time gap for emergency stopping in manual driving scenario varies between 1 to 2 seconds [96], in a recent CACC field study, 55% drivers following the lead vehicle required 0.55 seconds headway [97]. As major benefits of CACC will be realized by vehicles following closely at a reasonably high speed, user willingness to follow closely is vital. Failure of CACC system due to inappropriate modelling of driving scenarios and related control strategies will force drivers to take back their control in a most dangerous driving condition in absence of collision avoidance application. Extensive real world testing of CACC system considering all possible driving scenarios such as roadway geometry, variation in speed limit/traffic controls, weather condition, driver characteristics (e.g., age, gender), traffic composition (e.g., pedestrian presence, vehicles with/without CACC system) will provide valuable insight in the development of dependable CACC systems that will reduce this risk.

Studies show that human performance degrades in a situation of automatic system failure compared to dealing with same situation in a manual driving condition [98]. Similar findings have been reported in other industrial settings, where higher human response time was observed in an automated operations scenario compared to a non-automated operations scenario during system failure [99]–[102]. Thus, the CACC system needs to be simple, reliable and trustworthy to address the higher driver reaction time during CACC operations [91]. Moreover, driver's failure to take action timely could be minimized by installing redundant low cost sensors (similar to ACC application) to take system control that will avoid collision in absence of driver's action.

CACC system also brings the risk of over-reliance on the system by its users. Improper understanding of functionalities, abilities and limitations might lead users to misuse, disuse and abuse the system [103], [104]. A driving simulator study reveals that humans trust increases with time when they have an accurate understanding of how a system works [105]. Under-reliance and over-reliance on automation contribute to several fatal accidents in other industrial setting [106], [107]. To eliminate these deficiencies, certified training program can be introduced with traditional driving training on CACC operational features, as well as regulatory initiative to harmonization of CACC system developed by multiple auto manufacturers will be critical. CACC system that is easily understandable with a clear description of its limitation and functionalities will be easy to adopt by mass users.

There are also concerns about carryover effects, i.e. how drivers will adopt to manual driving immediately after CACC driving. One study reports that drivers tend to maintain short time gaps even during non-platooning conditions, which is a major safety concern [108]. This drawback could be addressed by providing frequent warning to drivers during non-CACC operations, not to follow the lead vehicle closely.

B. Workload and Distractions

CACC system improves traffic flow by allowing short time gaps, which also reduces driving workload as the system takes over the vehicle's control. However, drivers still need to monitor the system continuously to respond to emergency situations [109], [110]. Although reducing workload could improve drivers performance, it has been reported in numerous studies that drivers mostly get engaged in non-driving tasks such as on-board entertainment gadgets and off-road objects [98], [100]–[118]. Due to distractions from non-driving tasks, drivers take more time to react to emergency braking than manual driving [112], [114]. Since an increase in reaction time due to automation will hinder the adoption of CACC in real world, human machine interface design that improve driver engagement need to be explored. Understanding of complex interaction of CACC design-operations and human interaction is the key. CACC system design may consider informing responsibility of drivers during CACC operations to keep the drivers attention that could reduce distractions, and will improve overall system safety.

C. Drivers' Behaviors in Traffic Stream

Transportation network level impact assessment of CACC systems requires accurate modeling of drivers' car-following and lane-changing behaviors, which are also the building blocks of any traffic micro-simulation model and other traffic operational evaluation tools. In the following two subsections, we will review potential implications of drivers' car-following and lane-changing behaviors due to CACC operations and will identify factors to be considered in network level CACC operations evaluation.

1) Car-Following Behavior: How drivers follow lead vehicle in a CACC platoon depends on drivers' car-following behaviors. The safety and operational performance, and stability of CACC platoon relies on the gap (time/distance) maintained by vehicles in a lane, which depends on driver characteristics, highway geometric characteristics and environmental factors etc. For manual driving vehicles, different car-following models entail the determination of multiple parameters to represent how a driver in the following vehicle interacts with the leading vehicle [119]. These driver behavior parameters are stochastic in nature depending on driver characteristics, and they have an impact on implementation of CACC strategies [120]. Van der Hulst reports that drivers tend to maintain longer headway when they are under fatigue or adverse driving conditions such as low visibility and night time driving [121]. Moreover, drivers with aggressive behaviors such as not wearing their seat belt follow cars more closely giving a shorter headway [122]. Thus, the selection of comfortable headway in a CACC platoon depends on diverse roadway and driver characteristics and weather conditions.

Drivers demonstrate better performance in the estimation of the following distance behind a leading vehicle (i.e. distance headway), but they show very poor judgment in the estimation of time headway [96]. Moreover, historical trend analysis reveals that time headway observed in today's traffic steams is much lower than that observed in the past [123]. It might be due to the fact that vehicle technology has improved significantly over the years, and traffic on today's roadways is more congested, which results in the shorter headway [96]. Distance and time headway exhibited by drivers depends on drivers' age and gender. Male and younger drivers tend to maintain shorter headway as compared to female and older drivers [124]. Thus, CACC operating parameters need to be customized for individual driver considering the diverse driver population characteristics in a CACC platoon.

A study on following distances of different types of leading vehicle found that drivers follow large trucks relatively close as compared to small vehicle/passenger cars [125], due to the fact that large trucks will take a longer time to break in emergency situation, which will allow following cars a longer time to react or stop [126]. On the contrary, another study observes that older drivers tend to maintain longer distances compared to younger drivers, and did not find any difference in following distance based on the type of the leading vehicle [127]. These conflicting findings warn us to identify and verify underlying true driver characteristics, which is a prerequisite for better CACC design. There are also misconceptions among drivers about their own driving skills. Drivers' perception about their own driving skill is always over-optimistic, while the perception of other drivers' skills is always underestimated [128]. Therefore, understanding of actual driver behaviors will help designing more reliable and efficient system. Numbers of electronic devices are growing in new vehicle models. Use of electronic devices, such as talking over cell phone while driving increase distraction, reaction time, and hence, substantially reduces driving performance [129]. However, though most drivers perform poorly during cell phone conversations, they grade themselves better than their actual performance [130]. This distractive influence is a concern for CACC systems, which may increase headway between vehicles in a platoon and reduce achievable roadway capacity [131], [132]. Different fields and simulation studies on driver behaviors suggest that CACC system design requires incorporating and modeling growing sources of distractions.

2) Lane-Changing Behavior: As CACC will enable vehicle platooning, one vehicle's decision to change lane will affect the stability of the platoon. Lane changing activities reduce roadway capacity and safety as it induces disturbance in the traffic stream [133]–[135]. Improvement in lane changing performance depends on the accurate modelling of asymmetric driver behaviors, drivers' gap acceptance, target lane gap availability, and vehicle characteristics [136]. Similar to the car-following behavior, lane changing behavior also depends on driver characteristics, e.g., younger and aggressive drivers are more likely to perform frequent lane changing [137], [138]. To accommodate leaving and entering vehicles in a CACC platoon, control strategies need to be designed to minimize disturbance to maximize roadway capacity.

In a platoon, if the lead vehicle decides to maintain a low speed, most of the following vehicles are likely to leave the platoon [139], as drivers want to reduce total travel time of a trip by driving at a higher speed [140]. This lane changing behavior is influenced by the variation in different drivers' preferred speed profile. As the lane-changing behavior is influenced by the perception of each driver about surrounding vehicles, drivers in a platoon may notice that vehicles in non-CACC lanes are moving faster as they observe a few fast moving vehicles in non-CACC lanes [141]. In this situation, drivers' understanding of potential gains of staying in a platoon such as higher average speed will influence the drivers' decision to maintain CACC platoon position [142]. On board feedback illustrating the expected benefit of staying in a CACC platoon, such as fuel saving, travel time savings could be used to influence drivers' decision. On the other hand, if drivers are more involved in non-driving tasks, it might reduce lane-changing as drivers are less attentive to the driving tasks and surrounding vehicles [111]. In this instance, this type of behavior might actually improve safety [92].

While in a dedicated infrastructure (i.e., separate lane or highway section), all vehicles operating in CACC can reach up to 8,500 vehicles per hour per lane [19], in typical highway with 100% CACC penetration, the capacity can reach up to 4,200 vehicles per hour per lane [15]. However, if vehicles leave CACC platoon frequently, the capacity of the highway will be reduced significantly as lane changing will increase the average time headway between vehicles. This disruption can be minimized by limiting the size of platoons and by giving advance warning to following vehicles [12].

D. Summary and Future Research

Driver behaviors are at the core of any potential connected vehicle application design and operations. Existing literature reveals the key challenges to be explored to realize the full potential of CACC systems for improved traffic operations and safety. A primary challenge of maintaining drivers' attention depends on accurate understanding of driver behavior during CACC operations. At the same time, the CACC system should be designed such that it does not create new sources of driver error/distraction. Artificial Intelligence (AI) based methods have been found useful and reliable in ITS for real-time traffic management [143]. These AI methods have great potentials to apply in CACC driver-support system design they incorporate knowledge from previous experiences and support improvements of these systems with new data obtained during actual operations. The major research topics to be explored in future based on literatures are—i) how CACC system interact with drivers to positively influence drivers' willingness to use CACC in different traffic conditions; ii) how to involve drivers in CACC operations to balance driving workload; and iii) how to develop strategies for CACC platoon formation size, and efficient ways for vehicles entering and leaving a platoon, and iv) how first generation of CACC enabled vehicles will operate with non-CACCC vehicles in mixed traffic stream.

IV. Controls

A reliable CACC system can keep the driver safe in bad driving environments such as heavy rain and fog by eliminating the deficiency of human drivers (e.g., poor vision) and possible human operating errors. Moreover, because of the better aerodynamic performance brought by the narrower inter-vehicle gap, a lower fuel consumption can be achieved, especially for heavy-duty vehicles such as trucks and vans [144]–[147]. In the following subsections, the implementation of different control strategies will be explored between connected vehicles in a platoon.

A. *Control System Modeling for CACC*

The CACC system became an upgrade from the ACC system by adding a feed-forward signal into the control loop. This method provides more information. For example, the acceleration information of the leading vehicle can be sent to the following vehicles through V2V communication so that a better system response (e.g., smaller headway and smoother operation) can be achieved.

All of the CACC vehicles in a platoon have the same objective to follow its leading vehicle with a certain distance, which is the acceptable/comfortable inter-vehicle distance determined by the spacing policy. There are two major spacing categories that adopted by existing car-following models. The first one is the constant distance category, which has a fixed desired inter-vehicle distance [148]. The second one is the velocity dependent spacing category, which determines the inter-vehicle distance based on vehicle velocity. For a vehicle i in the platoon, the velocity dependent spacing policy relates the desired inter-vehicle distance with time headway [149]:

$$d_{r,i} = r_i + h_{d,i} v_i \tag{1}$$

where $d_{r,i}$ is the desired inter-vehicle distance between vehicle i and its leading vehicle, r_i is the standstill distance, $h_{d,i}$ is the time headway, and v_i is the velocity of vehicle i. Then, together with the actual distance detected by the onboard vehicle sensors, e.g., Radar or Lidar sensors [150], the spacing error can be calculated.

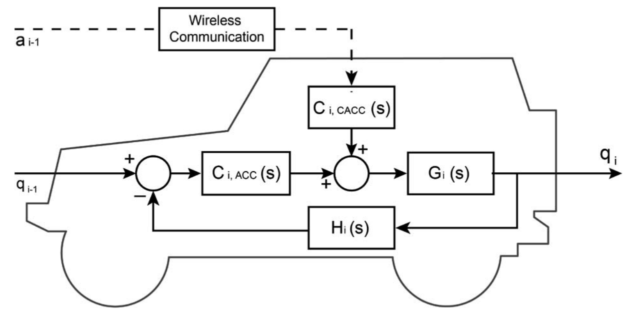

Fig. 1. Block diagram showing the control structure of one vehicle in a CACC platoon with predecessor following (PF) information topology.

The vehicle longitudinal dynamic model provides the implementation environment for CACC systems. In [151], the vehicle longitudinal dynamics are described as a nonlinear model, which evolves the engine, road and tire resistance, gravity and aerodynamics drag. This model is close to the real vehicle dynamics since it takes many vehicle and environment parameters into account. However, such a complex model brings inconvenience to system analysis. In [152], a linearized model for the vehicle longitudinal dynamics is presented, which is frequently used in ACC and CACC studies. In this model, vehicle position, velocity and acceleration are used to form the state variables, and therefore, the state space representation in terms of velocity, acceleration and jerk is given in the following form:

$$\left.\begin{aligned} \dot{q}_i &= v_i \\ \dot{v}_i &= a_i \\ \dot{a}_i &= -\frac{1}{\eta_i} a_i + \frac{1}{\eta_i} u_i \end{aligned}\right\} \tag{2}$$

where q_i is the vehicle position, v_i is the velocity, a_i is the acceleration, η_i is the internal actuator dynamics parameter, and u_i is the system control input. There are also some transformations of this dynamic model. In [150], the state variable, q_i, is substituted by the actual inter-vehicle distance, $d_i = q_{i-1} - q_i$, while [149] has changed this state to the spacing error $e_i = d_i - d_{r,i}$.

The CACC controller design depends on the vehicle information flow topology. The topology determines the connection among the CACC vehicles in a platoon. There are plenty of CACC information flow topologies studied by researchers. The major types of information flow topologies are summarized in [152], such as predecessor following (PF), predecessor-leader following (PLF) and bidirectional (BD). The most commonly used topology is predecessor following (PF) where the following vehicle only receives communication signal from its predecessor. The controller under this type of topology is formed by two parts: feedback ACC $(\mathrm{C}_{i,\mathrm{ACC}})$ and feed-forward CACC $(\mathrm{C}_{i,\mathrm{CACC}})$. The system block diagram is shown in Fig. 1. Both the CACC and ACC inputs can be seen as acceleration signals that act as an input to the vehicle dynamics. The conventional ACC controller is usually a simple proportional-derivative (PD) controller or proportional-integral-derivative (PID) controller. The CACC controller is designed to process the wireless communication signal. A feed-forward filter is used to process the acceleration data that are transmitted from the preceding vehicle to obtain the CACC control input. This design has been discussed in [146], [149], [153]. The feed-forward filter is built into the system based on a zero-error system requirement [145]. The predecessor-leader following topology is adopted in [148]. Under this type of topology, the controller takes two error signals into account since the subject vehicle has communication with both its predecessor and leader in the platoon. PID controller is also applied in the controller design. Bidirectional topology is implemented in the CACC system design in [154], [155]. This method allows the subject vehicle communicate with its adjacent vehicles. In [154], the controller uses the front and rear spacing error as the feedback signals. A parameter ϵ is used to change the ratio between the front gain and the rear gain, while [155] defines the front gain and rear gain separately.

Other control methods are also investigated for CACC systems. The authors in [156] modify the network consensus control algorithms into a weighted and constraint framework. The control system can coordinate all the vehicles in the platoon to achieve a desired distributed pattern. A distributed control protocol based on distributed consensus strategy is derived in [157]. This method considers the heterogeneous delay of the CACC communication. The authors prove the system's stability under disturbance.

Within the system dynamics, the vehicle actuator delay is taken into account for practical implementation. To get a closed-loop model, the authors in [149] use the kth-order Padé approximation to approximate the actuator delay so that the time delay can be formed into a finite-dimensional model. Details about this approximation approach can be found in [158]. With this model, a connected CACC vehicle string can be created using a discrete-time modeling method. A similar approach is used in [150], [153]. In [152], a two-loop control architecture was adopted. The outer loop controller uses the same spacing policy as described above. The acceleration controller combines the sensed data (e.g., inter-vehicle distance and velocity) and the communication data to generate an acceleration input for the inner loop. The inner loop utilizes the sliding mode control (SMC) based on a simple vehicle model.

The working environment for autonomous driving technologies such as ACC and CACC is not always perfect. The control systems need to have the ability to deal with stochastic disturbance and uncertainties from either the drivers or the system itself. In [159], a reinforcement learning approach is proposed to design the CACC system. The system is modeled as a Markov Decision Process (MDP), and the authors incorporate the stochastic game theory into the system to improve the CACC performance. Simulation results show that small disturbances are damped through the platoon. In [160], the authors propose an online fuzzy controller in order to adapt to environmental uncertainties during driving. The authors in [161] investigate the uncertainties in communication network and sensor information. They model the uncertain parameters and delays of the system using Gaussian distribution and utilize this model to approximate the minimal time headway for safety. The stochastic delay of communication is considered in [162], where the delay is incorporated in the system dynamic model. Both the plant stability and string stability are analyzed considering the probability distribution of the stochastic delay. The necessary conditions for plant and string stability are also derived. In [163], supervised adaptive dynamic programming (SADP) is adopted in an ACC system to deal with the stochastic driving situations. The authors test the proposed algorithms on different scenarios such as stop & go, emergency braking, cut-in and changing driving habit.

Although considerable efforts have been made for CACC controller design and provided a solid foundation for the improvement of CACC performance, more practical factors such as traffic conditions and human factors need to be explored to realize the full potential of CACC systems.

B. String Stability

The basic requirement of applying CACC to vehicles is to have a stable system performance to ensure the safety and comfort of drivers and passengers. In particular, string stability is an important performance criterion for the CACC controller design [146], [164].

The string stability of the vehicle platoon requires that either the vehicle's spacing error, states or the control input does not amplify upstream through the platoon [152], [153]. If the vehicle platoon is not string stable, a small perturbation on one vehicle can propagate through the platoon [165] and cause uncomfortable driving experience or even dangerous situations. There are three major approaches for string stability analysis, i.e., the Lyapunov stability approach, the spatially invariant systems approach and the performance-oriented approach. In [166], the author uses the Lyapunov stability approach to analyze the string stability of an interconnected system. Sufficient "weak coupling (relaxing formation rigidity)" conditions are derived so that the interconnected system, e.g., CACC, is guaranteed to be asymptotically stable and remain string stable under perturbations. The second approach mainly focuses on infinite-length platoon. It uses Fourier transformation on the system state space and assesses the string stability by analyzing the corresponding eigenvalues [167]. Then, the performance-oriented approach, in particular, is the prevailing method for easy and intuitive analysis of string stability of the highway traffic flow by considering string oscillation. The following transfer function based criterion has been widely used in this method:

$$SS_i = \frac{\Lambda_i(s)}{\Lambda_{i-1}(s)} \tag{3}$$

where $\Lambda_i(s)$ and $\Lambda_{i-1}(s)$ are the Laplace transforms of the states of vehicle i and $i-1$, i.e., the inter-vehicle distance error (E), vehicle state (X), or vehicle control input (U). The paper [153] investigates string stability using the frequency domain approach under three scenarios including constant velocity-independent inter-vehicle spacing, velocity-dependent inter-vehicle spacing with ACC setting, and velocity-dependent inter-vehicle spacing with CACC setting. Results from experiment validations show the ability of CACC to achieve better inter-vehicle distance, time headway, and string stability from a frequency domain perspective. The magnitude of string stability transfer function is used to develop sufficient conditions for string stability [149], [150]. Constant velocity-independent inter-vehicle spacing scenario (i.e., time headway $h_i = 0$ sec) is the simplest condition for system setting; however, it can only guarantee the marginal string stability, i.e., $\sup|SS_i(j\omega)| = 1$, with or without the feed-forward filter. For the velocity-dependent inter-vehicle spacing scenario, with both ACC and CACC systems, the string stability can be achieved if $\sup|SS_i(j\omega)| < 1, \forall\, \omega$, which means that the error of the system will not amplify upstream the platoon. If the error signal keeps amplifying in upstream the platoon, i.e., $\sup|SS_i(j\omega)| > 1, \forall\, \omega$, the string will be unstable [168]. In addition, [169] proposes a new $\mathcal{L}_p$ string stability criterion, which can be applied on both linear and nonlinear systems. It considers system initial conditions, external perturbations, and constraint on time headway. The string stability of CACC system with homogeneous and heterogeneous traffic has been studied in [146]. The authors derive conditions on the time headway and control gain under which the string stability can be guaranteed.

The effects of different information flow topologies on CACC string stability are investigated. The PF topology only considers the error between the preceding and following vehicles [153]. The critical values of time headway and control gains are derived from the analysis of the string stability transfer function. Thus, the string stability can be guaranteed by tuning system parameters, e.g., time headway and controller gain. For the LPF topology, the authors in [170] analyze the string stability transfer function and the spacing error dynamics. The distribution of the predecessor error gain and the leader error gain need to be well designed so that the system can meet the string stability criterion and the spacing error magnitude can be bounded. The CACC string stability under BD topology is studied in [171]. The analysis method is still investigating the string stability transfer function. The design of control gain can influence the system by determine whether the maximum magnitude of string stability transfer function can meet the criterion. In this paper, the corresponding control gain requirements are also given.

The authors in [172] studied the sufficient conditions for string instability in frequency domain. The threshold for exponential disturbance amplification is discussed. Other than the conditions, the authors also find out that extra communication range can significantly damp the disturbance and adding more communication dimensions can help to avoid string instability. String instability always comes with shockwaves, which is the main factor that causes the drivers and passengers' uncomfortable driving experience. For manual driven vehicle systems, due to the reaction delay of human drivers and the accumulation of the inter-vehicle distance error, drivers need to adjust their speed more frequently so that more braking and accelerating actions will be applied on vehicles in the platoon. These actions are the cause of shockwaves. With a smaller inter-vehicle distance, the shockwave is more likely to occur. The study in [173] show that a CACC system can reduce the shockwave phenomenon in mixed traffic. This is because 'knowing' the status of the preceding vehicle, each one of the following vehicles can reduce the action of braking and accelerating. Thus, under CACC, shockwaves are damped even with a small inter-vehicle distance applied on the platoon. In paper [12], the author investigates the number of shockwaves as the stability criterion during the simulation. The result shows with 60% of CACC penetration, the traffic stability and throughput can be improved significantly. The author in [173] analyzes the effects of CACC on the traffic flow based on a field-tested ACC system. The simulation results show that CACC can damp the shockwaves quickly even at low market penetration (50%).

Other than the string stability criterion, there are several studies that focus on the stability margin of CACC systems. Stability margin is defined as the absolute value of the real part of the least stable eigenvalue of the system state matrix. It provides an alternative for the CACC system stability analysis. In [174], the system control is designed based on a small mistuning of the control gain to improve stability margin of the closed-loop platoon. The authors in [175] design a mistuning-based control gain using a partial differential equation (PDE) model, and the resulting controller improve stability margin in the presence of small perturbations. The paper [176] discusses the network effects on stability margin of a platoon with a large amount of vehicles. Different information flow topologies are also considered, e.g., [177] discuss the stability margin of a platoon with bidirectional topology and the corresponding control law.

Existing works on stability analysis of CACC systems still lack investigation of more comprehensive scenarios such as mixed traffic and vehicle switching between different levels of automation. To fill this gap, CACC systems need to be able to switch between different scenarios and adapt to uncertain environment while guaranteeing stability.

C. Communication Effects on Control Design

A CACC system with nonlinear vehicle dynamics may perform unstably while there is a non-ideal wireless communication environment. The delay of the wireless communication system is considered in the design of the feed-forward filter [146], [153]. The communication delay could cause the instability of the system. However, for CACC systems, even with the presence of communication delay, the minimum time headway that can maintain string stability is still smaller than that in ACC systems, which confirms the benefits gained by using the wireless communication in CACC systems. In [150], the authors discuss experiments on the implementation of CACC into passenger cars and prove that the CACC system is capable of reducing the time gap between vehicles and still maintain string stability. The experiments show that the time gap of vehicles could be less than 0.5 second with optimal wireless connection. Saturation is shown in the implementation of CACC on actual vehicles during experiments [145]. The efficiency of data transmission has been studied by evaluating the effect of packet loss on string stability. When experiencing unreliable wireless connections, some of the CACC vehicles will turn into ACC vehicles due to the disconnection of data transmission. The impact of degradation of a CACC system (dCACC) is studied in [178]. A graceful degradation technique is proposed, which uses an estimator to estimate the preceding vehicles acceleration rather than simply using the transmitted acceleration signal. To estimate the acceleration of the vehicles near the following vehicle, a multi-object tracking algorithm and a continuous-time Kalman filter are used. Compared with the approach of simply changing the system market penetration rate, this approach considers the change in the number of CACC vehicles in platoon activity. Therefore, it can give us a better understanding of how the system is going to respond if some of the CACC vehicles in a platoon are degraded. A CACC fallback scenario is set and the experiment shows the benefit of applying the graceful degradation technique [178]. Some recent works have also focused on CACC vehicles' on-board sensor failures. A sampled-data switched system framework is used to analyze the impacts of sensor failure on CACC system stability [179]. A similar approach can be used on the study of CACC communication failure to reduce the negative effects of bad wireless connection. Therefore, control laws that take into account communication effects such as delays, packet dropouts are a very important step to establish reliable CACC systems.

D. Human Factors Effect on Control Design

According to the definition of vehicle automation [10], [11], ACC and CACC with lane kept assistance belong to level 2 because both ACC and CACC still require the driver to constantly monitor the traffic condition while having the autonomous driving function. However, handing over the control power to the autonomous system does not mean that the control design can be separated from a human driver. To achieve a better human acceptance on the CACC system, human factors have to be considered in the control system design.

Because very few works have studied human factors in the design of CACC systems as discussed in Section III, we have taken this opportunity to summarize the main results from the implementation of human factors in ACC system design. These works focus on human-like autonomous vehicle control designs and seek to make the driver feel comfortable and trust the system. We summarize these works into two categories: the online control approach and the offline control approach.

The online control approach directly learns from the human driver to gain information that can be used in the controller. In this way, the controller can act more like a human driver and adjust the autonomous driving in real time. In [180], [181], the ACC systems can obtain human driving parameters, for example the inter-vehicle spacing and time headway, through some self-learning techniques, such as data sampler, artificial neural network and recursive least-square algorithm. The authors in [182] use probabilistic neural network to assess the driver's fatigue level and adjust the ACC's parameters accordingly. In [183], the control system keeps the driver in the loop and uses an adaptive fuzzy logic controller to determine the driver's type and change the controller of vehicle accordingly. Moreover, optimal control methods such as model predictive control (MPC) are utilized in [184] to achieve human-like ACC. In [185], an adaptive optimal control approach based on Q-function is used to allow the ACC system adapts to different driver habits. The offline control approach does not vary during driving. The data used in the controller design can be collected from a driving simulator or real world experiments. In [186], the preprocessing training data are used to gain fuzzy rules for ACC system design. In [187], [188], real world driving data are collected and analyzed to infer driver characteristics and applied into the ACC design. Furthermore, a fuzzy logic controller, which is based on a fuzzy coprocessor, ORBEX [189], is adopted in [190], [191] to emulate human driving behaviors.

Nowakowski *et al.* studied driver acceptance of the inter-vehicle time gap, which is less than one second [192]. With the experiment and survey, the results show that CACC system is more likely to give drivers confidence to set the time gap into a short range. If the system can be designed based on real human driver data and behavior, we can assume that the system can achieve better driver acceptance.

Furthermore, human trust in automation is another key factor that determines human use of automation and should be considered in the CACC system design. Trust is the central determinant of human acceptance and, hence, allocation of autonomy. Thus far, little has been done to implement the human trust factor into system design. Some pioneer works have focused on the study of trust in multi-robot systems and manufacturing and can be used a starting point in the CACC system design [193]–[195].

Multiple approaches have been proposed to incorporate human factors into ACC or other autonomous vehicle control technologies. However, there are very few works specifically focus on CACC systems. Due to the characteristic of short inter-vehicle gap of CACC platoon, human acceptance on the system is an important problem for the CACC study. Simply enlarging the car-following gap cannot solve this problem because we still want to keep the high traffic efficiency that CACC system brings to us. A potential solution is to take into account both riding comfort and driver psychology in the controller design. The feedback from the riding comfort assessment and the physiological car-following model can help to optimize the system performance and gain better human acceptance. Similar to the human-like ACC system design, the learning techniques can also be applied on CACC system to make the controller adapt to each individual driver.

E. Control Model for Merging and Lane Changing

Merging and lane changing are two common scenarios that drivers will experience during their daily drive on highways. Simulations based on these two scenarios are presented in [196]. In [197], a constrained geocast protocol is proposed to support the merging action in the CACC string. This protocol helps to target vehicles according to their predicted positions instead of the current positions. RSUs are used to detect the merging vehicles and create merging requests (MRs), which contain the position information and the required space of the merging vehicles. All of the MRs are sent within one merging message with proper constraints. Based on this message, the predicted position of the merging vehicle can be calculated, which allows the CACC control module to create suitable conditions for the merging vehicle to complete the action. This method was compared with a simple broadcast protocol, and the result shows that both of them can meet the requirement of the merging scenario. However, the constrained geocast protocol performs better at a higher traffic density [197]. In [198], "Demo 2000 Cooperative Driving" was used in five testing vehicles to simulate the merging and lane changing scenarios.

F. Summary and Future Research

Current works mainly focus on one or two aspects, e.g., communication and human factors, and their respective effects on CACC controller design. The results from these works provide good contributions to the CACC system development but are not close enough to the real-world traffic environment. It is necessary to conduct more comprehensive studies with integrated communications, human factors and control methods to understand and analyze more practical driving situations. First of all, the performance of CACC systems in mixed traffic environment needs to be studied. Since the CACC market penetration cannot reach a high level in a short period of time, the mixed traffic scenario will always be the common working environment for CACC systems. How to design a CACC system to guarantee stability under the mixed traffic environment, in bad communication connections or vehicle cut-in scenarios, should be an important topic for future CACC study. This development can provide a solid background for the implementation of CACC system into production cars. Next, in real CACC vehicle driving experience, the drivers should have the freedom to decide whether to switch between different levels of automation under different traffic conditions. The CACC system needs to ensure the platoon stability and the vehicle performance with all the possible switch actions, e.g., multiple drivers' switch actions within the CACC platoon, even in a mixed platoon. Finally, the design of human-aware CACC system is another topic that can affect the implementation of this system into production and hence market penetration. It is important to identify the optimizing factors for control system designs and setups that can lead to a better human acceptance on CACC. The goal of the CACC design should be giving the system the ability to adapt to each individual driver and gain trust from the drivers. One intuitive example can be incorporating learning techniques into CACC systems to learn the driver's preferences and adjust the control system accordingly. Meanwhile, human psychology model should also be implemented in the system to provide extra human trust information to the system. This topic requires the human psychology model takes the vehicle dynamics into account, e.g., the vehicle states, and the control system can also optimize its behavior based on the psychological feedback. Thus, the application of such CACC system in passenger cars will more tend to be accepted by the market.

In summary, the main topics on the CACC system control design that are worth investigating in the future are—1) the compensation of bad communications, 2) the consideration of more practical driving scenarios such as mixed traffic and switched levels of automation, and 3) human-aware CACC system design.

V. Conclusion

Limited financial resources to build additional highways motivate transportation professionals to explore technology solutions to improve traffic flow and safety. The CACC application has the potential to increase the traffic capacity dramatically given that penetration level of vehicles with the CACC functionality is high in the traffic stream. CACC system should have reliable communication to maintain connectivity between vehicles, keep drivers behind the wheels attentive to the driving task, and enable the execution of appropriate control strategies in response to changing traffic patterns and demands.

The first critical step in realizing a reliable CACC system is to establish efficient and robust communications between vehicles under highly dynamic environments. The applicability and potential drawbacks of different routing algorithms in CACC systems were identified in this paper. Based on the drawbacks of existing vehicular networking protocols, the future research for CACC routing support must address the proper scheduling of vehicles in a platoon, and workload distribution between on-board and roadside units.

Driver characteristics are a complex part of the CACC system design. A small following headway in CACC platoon will create a safety risk if the drivers get distracted and cannot respond on time upon system requests. The primary challenge of maintaining drivers' attention depends on accurate understanding of driver behavior during CACC operations. Thus, a CACC system should be designed such that it eliminates negative consequences of automation. Also, training CACC users about system capabilities, limitations, and drivers' responsibilities are critical to avoid over-reliance on the system.

CACC control technologies are not market-ready due to their lack of ability to address diverse real-world driving conditions. For instance, existing studies on CACC rarely address human factors in the control design. For CACC systems to be widely adopted in future transportation networks, these additional factors should be considered in a CACC controller design.

Though, this paper is mainly focused on three major CACC system design related technical issues, there are other issues, such as legal aspects of any crashes due to the failure of the system, users' privacy and security, technology certification, user training, that are out of scope of this paper and could be explored in another paper.

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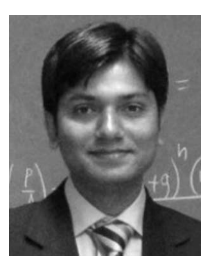

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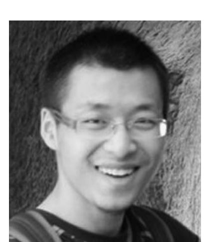

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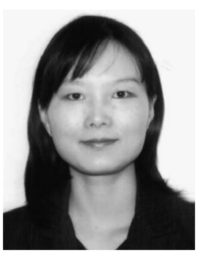

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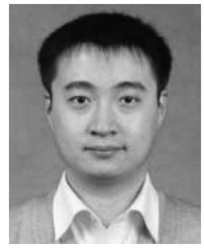

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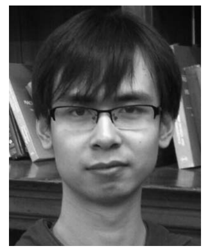

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