Lane Change and Merge Maneuvers for Connected and Automated Vehicles: A Survey

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***Abstract*—Intelligence in vehicles has developed through the years as self-driving expectations and capabilities have increased. To date, the majority of the literature has focused on longitudinal control topics (e.g. Adaptive Cruise Control (ACC), Cooperative ACC (CACC), etc.). To a lesser extent, there have been a variety of research articles specifically dealing with lateral control, e.g., maneuvers such as lane changes and merging. This paper provides a survey of this particular area of vehicle automation. The key topics addressed are control systems, positioning systems, communication systems, simulation modeling, field tests, surroundings vehicles, and human factors. Overall, there has been some successful research and field testing in lane change and merge maneuvers; however, there is a strong need for standardization and even more research to enable comprehensive field testing of these lateral maneuvers, so that commercial implementation of automated vehicles can be realized.**

***Index Terms*—Cooperative adaptive cruise control (CACC), light detection and ranging (LiDAR), lane change and merge, differential global positioning system (DGPS), platooning, dedicated short range communications (DSRC), managed lanes, model predictive control (MPC), real time kinematic (RTK).**

I. Introduction

ROADWAY driving is a commonplace aspect of modern life, yet motor vehicle accidents are the leading cause of unintentional injury and death [1]. In fact there were 30,800 fatal car crashes in 2012 alone [2]. One of the more taxing and dangerous aspects of highway driving are lane change and merge (LCM) maneuvers. Annually, between 240,000 to 610,000 crashes are reported to the police due to improper LCM execution [3].

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Intelligence in vehicles has developed through the years as self-driving expectations and capabilities have increased. First was Cruise Control and Lane Following. The next step in the "evolution" of intelligent vehicles is the capacity of automated or assisted large lateral control maneuvers, such as lane changes. As the practically of vehicle platooning is becoming realized, research is processing toward applicable topics like CACC lane change and merge. A platoon (or convoy) could be considered as "loosely coupled" or "tightly coupled" depending on their control strategy. Research on CACC lateral maneuvers on a variety of roadways supporting collaborative driving, or a possible future automated highway system (AHS) framework is a practical step toward successful platoon implementation because is focuses on everyday road operations like vehicle overtaking, highway entry and exit, and adjusting paths to clear space for emergency vehicles.

Lateral maneuver research is a challenging undertaking that requires exploration of solution spaces to achieve optimal safety, mobility, and environmental factors. Although much research has focus on the longitudinal control of vehicles and platoons, researchers are recognizing the significance of the total motion of collections of vehicles as a means of revolutionizing traffic management.

Research on control systems, positioning technology, and communication standards have laid out much of the ground work necessary to achieve success in preliminary testing; however, more research is needed for comprehensive field testing of lateral maneuvers such as lane change/merge procedures. Although many technologies have been proposed, a limited number are recognized as effective. There are good simulation modeling packages available that have given evidence of success with platooning and collaborative driving. There have even been successful field tests performed for some of the newest research concepts. CACC lane change and merging is quickly becoming a feasible operation for our road networks.

The U.S. National Highway Traffic Safety Administration (NHTSA) has defined four different levels of automation that help classify various vehicle automation systems [4]. Level 1 is defined as a system with a single specific control function, e.g. Electronic Stability Control. Two control systems designed to be used in unison (e.g. Adaptive Cruise Control (ACC)) to be used with a Lane Keeping Assist (LKA)) are contained in Level 2. Under Level 3, drivers will be able to completely relinquish control during specific traffic scenarios. Finally Level 4 is defined as a system capable of complete autonomous operation. In this survey, there is an emphasis on Level 1 automation, but Level 2 is also incorporated. Level 3 and Level 4 automation are outside the scope of this report as the primary goal is to provide references for systems designed to be implemented over the next five years. Both national and international research are included. Freeways are the primary focus, although other roads such as arterials and urban roadways are also briefly addressed. In regard to control systems, there is a focus on the implementation of automated lane change and merge. However, all the models will be considered for the implementation including models for the lane-change decision-making process, models for different trajectories of lane changing in order to find optimal trajectories with free-collision, lane-change models and the dynamic models of vehicles for the controller design. Finally, passenger vehicles are the focus, but research involving heavy-duty vehicles is also included.

The primary technology required for the addition of lane change systems to the existing automation architectures is technology that can judge the vehicles position/speed with respect to both its current lane and its intended lane. This could be based on computer vision systems such as those used in lane departure warning systems. Another method would be to do this in absolute coordinates using a precise measurement system (e.g., inertial navigation aided by a Global Navigation Satellite System (GNSS) coupled with high-resolution maps. If automated lane changes are to be accomplished at predefined locations (e.g. shifting to an exit lane or predefined merge points), a number of other technologies can also be considered. Other sensing and communication technologies may also need to be utilized for safety, once additional traffic is admitted. Additionally, if the lateral control is intended to be automated and not merely an alert system that expects the driver to handle the actual performance of lateral maneuvers, then a robust steering assist system will need to be implemented.

The remainder of this paper is organized as follows: Section II presents a brief overview of vehicle positioning systems. Section III discusses the communication architecture that can be used to enhance vehicle automation, e.g., CACC platooning. Control system is introduced in Section IV. Human factors in driver assist systems are presented in Section V. Work in simulation modeling and field testing are documented in Section VII. Vehicle surroundings and environment are discussed in Section VI followed by the conclusions in Section VIII.

II. Vehicle Positioning Systems

Vehicles that have to perform lane change and merge need to have positioning systems. There exist various technologies to provide both absolute position and relative positions [5]. Radar, lidar and vision systems can provide relative measurements with respect to lane markings, GPS and a map (detailed enough to lane level resolution) can aid in a lane change (weather the lane is marked or not.)

A. Radar/Lidar

ACC was key milestone on the road to collision avoidance systems. The critical path to ACC systems was the development of an automotive component capable of detecting various targets ahead of the host vehicle. Widmann *et al.* made a comparison between ACC system performance using lidar and radar [6]. Their results show comparable performance with both sensor sets. Recent advancements in lidar systems have shown an improvement over radar systems. Radar systems provide a direct measurement of the Doppler shift, which yields a measurement of the relative speed and detected object (other vehicle). Computer vision systems are also now being used as part of commercial ACC systems. Additionally, radar systems have a longer detection range allowing ACC controllers to react more quickly to approaching vehicles. Due to the growing demand for ACC systems, new methods of detecting and tracking objects in front of the host vehicle are necessary. Systems have been developed that are capable of providing the necessary measurements for both ACC and pre-crash safety [7]. This system uses a switched phase multi-antenna array to aid in the detection vehicles at long range as well as distinguishing between preceding vehicles and those in adjacent lanes. Lane change maneuvers with ACC systems require accurate and fast tracking of detected vehicles as well as the separation of these detected vehicles into groups that are likely to have an impact on lane change or merging decisions. Tracking algorithms have been developed that use block matching methods to divide the road into sections based on lane width [8]. By dividing the radar beam range, this method allows for faster tracking of vehicles due to the necessity of only checking adjacent blocks to the last reported position of preceding vehicles. This tracking method allows for faster reactions from longitudinal controllers.

Light detection and ranging (lidar) is one such sensor technology that is used in some object and lane detection algorithms. It emits a focused beam of light (a laser); based on the returning beam, the distance between an object and the lidar can be calculated. There are many different lidar technologies and techniques used for determining this distance. Some lidars known as continuous-wave lasers, look at the phase shift in the light beam itself, while others, often known as pulse lasers, simply count the time interval between transmission and reception [9]. The former is a more common type of lidar in the vehicle safety field, and thus is more commonly used for lane level positioning. Because a pulsed laser determines distance based on a time interval, there are several factors that affect the obtainable accuracy, precision, and range of a lidar system, such as how fast the timer can operate, the maximum number of bits available to store a count, pulse rate, laser power, and detector sensitivity [9].

Lidar scanners also return a reflectivity measurement, which allows for the detection of lane markings due to the relative color difference between the road surface and painted lane markings. Algorithms have been developed that are capable of calibrating a lidar while simultaneously providing relative lane positioning data [10]. Systems similar to lidar have been developed which allow enforcement officials to detect the relative position of two vehicles in adjacent lanes in tailgating scenarios [11]. By detraining relative laser angles between vehicles the system can detect following distance. Relative vehicles' speed data is then fused to find acceptable following gaps to determine if a tailgating situation has occurred.

B. Computer Vision Systems

Lane departure warning (LDW) systems have had great success in terms of the reduction in accident rates. These systems primarily use computer vision technology to determine the position of the host vehicle relative to lane markings. Due to the success of these systems, LDW and lane keeping techniques are becoming more prevalent in new vehicles. The vision systems required by these technologies also give vehicles much greater capabilities in terms of relative positioning between vehicles. Computer vision capabilities are also now being used in ACC systems.

1) Camera Systems: Camera vision has already been implemented in LDW systems in commercial vehicles. These systems detect when the vehicle has left or is about to leave a lane and emit a warning to the driver. One such system proposed by Lee *et al.* incorporates a perception-net to determine the lateral offset and time to lane crossing (TLC), which warns the driver when a lane departure is imminent or may soon take place [12]. A fuzzy evolutionary algorithm was used by Kim and Oh to determine the lateral offset and TLC using a selected hazard level for lane departure warning [13]. Another LDW system [14], used a linear-parabolic model to create a LDW system using lateral offset based on the near field and far field. For the near field close to the camera's position in a forward-looking camera, a linear function was used to capture the straight appearance of the road close to the car. For the far field, a parabolic model was used to model the curves of the road ahead. In their following paper, Jung and Kelber used their system with the linear-parabolic model to compute the lateral offset without camera parameters [15]. Hsiao and Yeh avoided the use of the Hough transform and instead relied on peak and edge finding, edge connection, line-segment combination and lane boundary selection for their LDW system [16]. In [17], optical flow was used to achieve lane recognition in poor weather conditions. In [18], an extended Kalman Filter was used to model the lane markings to search within a specified area in the image so that far lane boundaries are searched with a smaller area than closer lane boundaries, thus reducing the impact of noise. Rose augmented this work by fusing an Inertial Measurement Unit (IMU) with camera vision in an Extended Kalman Filter [19].

C. Global Navigation Satellite Systems (GNSS)

Global Navigation Satellite Systems such as the U.S. Global Positioning System (GPS) combines a space segment and control segment to provide the receivers with radio signals that can be tracked to give a position solution for each receiver [20]. The GPS receiver can only calculate a pseudorange due to the corruption of the timing with atmospheric delays and receiver clock errors. In order to find a unique position solution the receiver must have measurements from at least four satellites. For typical satellite geometry this will result in horizontal position errors near 10 meters and vertical position errors near 13 meters [21].

In order to limit the position errors of the standard GPS solution, differential GPS (DGPS) techniques are used. DGPS takes advantage of the common mode error sources experienced by receivers operating in close proximity. The signal delays introduced by the atmosphere are highly correlated for receivers separated by several kilometers or less. The residual satellite clock errors after correction are also nearly identical. Measurements from two receivers are differenced to mitigate these common mode errors. DGPS methods incorporate the GPS pseudorange measurement, the carrier phase measurement, or both [22].

The carrier phase measurement is an accumulation of the cycles of the GPS sinusoidal carrier from the time of signal acquisition to the present time. This phase shift can be measured with significantly higher accuracy than the pseudorange (to within five millimeters [23]) but the absolute measurement contains an ambiguous number of carrier cycles. With accurate estimates of the carrier phase integer ambiguity, the relative position vector (RPV) between two GPS receivers can be estimated to within centimeters of the true value.

1) RTK: Real time kinematic (RTK) systems exploit the accuracy of the carrier phase measurement to calculate highly precise global position estimates. This is accomplished by combining measurements from a static base station at a known position with measurements for roving GPS receiver in the area. The base station broadcasts its position, pseudorange measurements and carrier phase measurements to the rover and the RPV from the base station to the rover is estimated. The RPV is then added to the position of base station resulting in a global position solution for the rover. This method results in a highly accurate global position solution of the roving receiver but requires the rover to be operating in proximity to a GPS base station.

2) DRTK: Global positions would need to be differenced from each other in order to determine the relative position between two vehicles. The global position solution given by using a static base station (RTK) solution is used for CACC Platooning or lane keeping systems. However, as CACC and lane keeping systems require relative position, different algorithms have been developed which maintain the high accuracy of the carrier phase measurements without the necessity of connecting with a static base station. A dynamic base station real time kinematic system for vehicle convoys has been proposed in [24]. This system is a combination of a Kalman Filter (floating point ambiguity estimation), the LAMBDA method (fixed integer ambiguity) proposed by Teunissen [25] and least squares estimation to find the RPV between the receivers. This method was shown to successfully guide vehicle convoys in situations where computer vision systems could not due to the limited visibility between vehicles.

III. Communication Systems

A key enabling technology of automated vehicle systems is wireless communication. CACC communications are enabled by Dedicated Short Range Communications (DSRC) radios (802.11p). Some alternatives to DSRC radios are 802.20 (3.5 GHz), 802.16 (WiMAX-MAN), and 802.15 (PANs-Bluetooth, ZigBee). However, NHTSA has mandated that V2V communication for safety take place using DSRC radios [26].

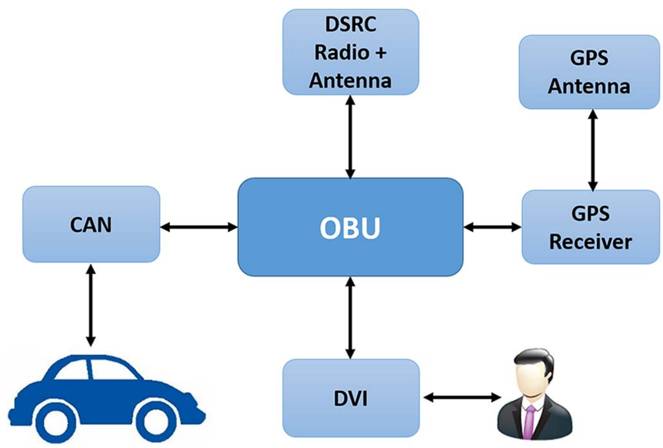

Fig. 1. Typical CACC on-board system.

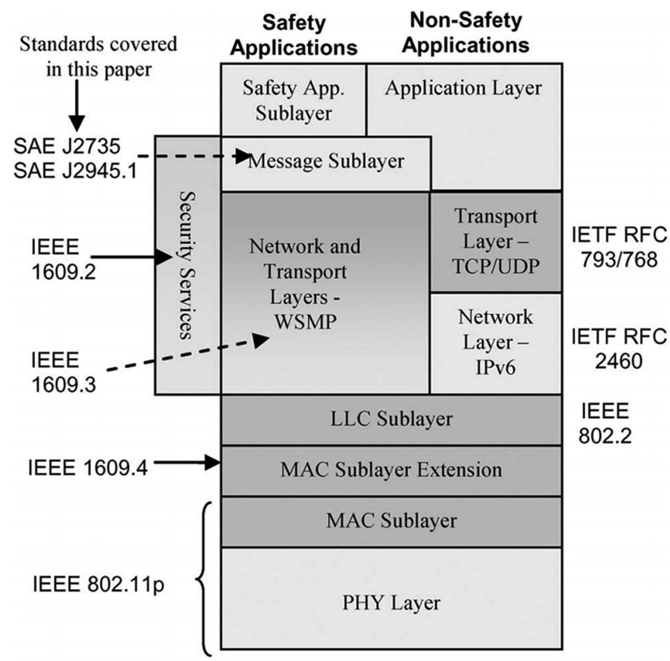

Fig. 2. Standard DSRC communication stack (from [31]).

The FCC has dedicated 75 megahertz of spectrum in the 5.9 GHz band (5.85–5.925) for intelligent transportation services as part of the Intelligent Transportation Systems national program [27].

The primary motivation for employing DSRC on vehicles is to enable collision prevention applications; however, other applications such as lane change or merging may be supported with DSRC on the service channels [28], [29]. Using DSRC, equipped vehicles broadcast their basic state information such as location, speed, and acceleration ten times per second. This critical vehicle safety information is conveyed in the format of the basic safety message (BSM) and is crucial for V2V and V2I safety applications. The DSRC equipped vehicles also receive these messages from similarly equipped neighbors. Each CACC vehicle has an On-Board Unit (OBU) consisting of a DSRC radio, GPS receiver, interfaces to vehicle sensors, and a human-machine interface [30]. In highway merging applications, a DSRC equipped vehicle will also receive safety messages and other types of messages from a DSRC Roadside Unit (RSU), which is considered vehicle to infrastructure (V2I) communication [29]. A typical in-vehicle system is shown in Fig. 1.

In this example scenario, the RSU detects merging vehicles, either by DSRC communication, or other detection methods such as radar and lidar and determines when and where a merging gap is needed. The RSU then sends this information out to the connected vehicles to inform them of the need for a merging gap in a merge request [28], [29]. In lane change applications, connected vehicles will send merge requests to platoons when they wish to join the platoon [28].

The protocol stack for DSRC communications is shown in Fig. 2. The PHY and MAC layers on DSRC utilize IEEE 802.11-p standards known as Wireless Access for Vehicular Environments (WAVE), which is a modified version of the IEEE 802.11 (WiFi) standard. The modifications guarantee fast reliable exchange of safety messages needed for vehicular environments [28].

When creating the 802.11 WAVE amendment for DSRC, the deviations from the 802.11 standards were minimized in order to encourage 802.11 vendors to add support for 802.11p. This facilitates operations in infrastructure and ad hoc modes, which map to V2V and V2I communications, respectively [32]. The middle of the DSRC stack employs standards defined by the IEEE 1609 Working group for safety applications, which includes BSM. For non-safety applications, DSRC also supports Internet protocols for the Network and Transport layers. At the top of the stack, a set of message formats that support vehicle-based applications is defined by the SAEJ2735 Message Set Dictionary. Common performance metrics for communication, identified by previous researchers, include network load, packet loss rate, and communication range [33]–[35]. Other implementation issues include network fragmentation, packet collision, shadowing, and signal interference [32], [36]. Due to the high speed environments present in merging applications, communication range and latency are highly important performance metrics. In an expressway setting with an elevated RSU, communication range has been demonstrated to be as high as 800 meters in either direction. Presence of foliage and buildings along the route shorten the communication range due to non-line of sight and multi-path reflections. Latency can be less than 100 milliseconds [30].

In the freeway merging application, network load, loss rate, and communication range was addressed by considering different message dissemination protocols which piggyback merging information on CACC BSM beacons [29]. Researchers have proposed sending merging information using ETSI CAM (Cooperative Awareness Messages) and DENM (Decentralized Environmental Notification Messages). It is claimed that the restricted unreliable protocol, which uses individual message routing over aggregated routing, is the best method to disseminate connected merging information. This protocol forwards merging data from one vehicle to another further down the direction of dissemination, which increases the notification distance in [37]. The transmission range will be negatively affected with a low vehicle density because of network fragmentation [28]; however, the suggested protocol is more scalable than other protocols because its added network load is lowest, about 5% loss rates for this protocol averaged around 4% in simulations except for cases with extreme low densities where network fragmentation occurs. With a density of 10 vehicles/km/lane the dissemination distance was on average 650 m, with vehicles traveling about 100 m before receiving merging information [38]. Yet another efficient method, multi-hop broadcast protocol (UMB) for inter-vehicle communication is designed to utilize the channel very efficiently in high traffic density areas [39]. As stated, connected vehicles broadcast and receive safety information multiple times every second over a range of several hundred meters. Under certain conditions, such as heavy braking, safety information may be sent out more frequently so vehicles can react more quickly. Upon receipt of these safety messages, a connected vehicle uses the information from the other vehicles to compute the trajectory of each neighboring vehicle, compares this with its own trajectory, and determines if any of the neighbors pose a collision threat. If the vehicle determines that there is a potential collision hazard, the on-board system either alerts the driver of the hazard or assists in controlling the vehicle [31]. The relationship between communication and automation for the highway merging application is similar except for the potential usage of a RSU. In this particular methodology for merging, the RSU can be placed close to the merge area and is responsible for tracking merging vehicles. The RSU is able to estimate when a merging vehicle will reach the merge area and at what speed. Based on this tracking data, the RSU calculates how large of a merging gap is required, and when the merging gap is required. The RSU then communicates this information to connected vehicles on the highway. The connected vehicles that receive this information use on-board computers to estimate whether or not they will be inside this merging gap and then take appropriate action to prevent themselves from being in the merging gap [28], [38].

IV. Control System

Lane change and merge control maneuvers contain both longitudinal and lateral aspects. In the simplest implementation, lane change can be accomplished by introducing a bias to the steering controller. As the bias is increased the vehicle will shift to one side. The steering control can rely on a sensing system providing relative measurements first with respect to the original lane and later, the new lane (at which point, the bias is removed). Lane changes for automated vehicles need to emulate human driving, so as not to bother the passengers with unexpected motions. Models of human for lane change behavior were utilized by Tomizuka [40] and Ozguner [41] in synthesizing automated lane change controllers.

Many theoretical and simulation studies have been conducted for the merging problem. As an example, consider the three vehicles shown in Fig. 3 that will be directly affected when the vehicle on the ramp attempts to merge. The ramp vehicle needs to maintain a certain safety distance from both vehicles in the main lane, so that it can perform a collision free and smooth merge operation. The problem arises when conditions

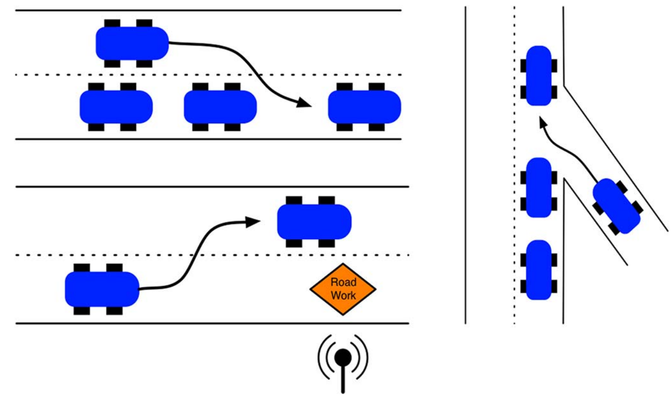

Fig. 3. Examples of lane change and merge maneuvers.

are such that there is not enough space for the ramp vehicle to merge in between the two vehicles. Therefore the ramp vehicle needs to slow down or stop to avoid collision and wait for an appropriate gap. If there is an open slot ahead of the vehicle on the main lane, or in the other lanes, this wait is unnecessary. It is desired for the merging vehicle to adapt to the main lane vehicles as much as possible to reduce negative traffic impacts due to main line vehicles changing speed or gaps. A merge control algorithm is thereby needed to solve this problem by adjusting the ramp vehicles approach speed and providing possible lane change or slow down commands to the vehicles in the main lane [42].

A. Longitudinal Control

Platooning is the most common CACC application. The longitudinal control involved in platooning consists of higher and lower control levels. The higher level is a supervisory controller which switches between the states of automated driving and pursues string stability. The low-level controller is essentially a throttle/brake controller that regulates the desired headway time or clearance.

A multiple of research has been conducted on the string stability of platoon [43]–[46]. The capability of the vehicles in the platoon in attenuating traffic shockwaves is defined as string stability. The longitudinal dynamics of the platoon are called string stable if sudden changes in the velocity of a vehicle at the front of a platoon are attenuated by the vehicles upstream in the platoon; if the changes are amplified, we call the longitudinal dynamics are string unstable [43]. For strong stability, spacing error must be decreasing propagated in the platoon so that the leading vehicle spacing error is equal to or less than the spacing error of following vehicle. Weak string stability refers to the property of limited spacing error so that maximum spacing error for following vehicles are equal to or less than the spacing error of the first vehicle behind the leading vehicle. String instability causes unnecessary traffic jams or oscillation in the platoon.

A macroscopic approach to model the dynamics of CACC traffic flow is developed based on a gas-kinetic theory in which the effects of ACC vehicles have been extended to account for the vehicle-to-vehicle (V2V) communication. Due to V2V communication, the CACC vehicle can follow its leader at a closer distance than the ACC vehicle. Also, based on the linear and nonlinear stability analysis, CACC vehicles enhance the stabilization of traffic flow with respect to both small and large perturbations compared ACC vehicles [47]. Theoretical results and experiments show that the string stability can be guaranteed when a constant velocity-dependent inter vehicle spacing criterion is applied, but string stability cannot be guaranteed when the intervehicle spacing is a constant velocity-independent [43]. Also, from a Networked Control System (NCS) perspective, network induced imperfections caused by limited bandwidth, multiple nodes sharing the same medium and transmission delays and losses were investigated in [48]. A CACC string modeled as a NCS model incorporating these effects was employed to study the string stability performance. The analysis showed that a high sampling frequency is desired to achieve string stability with relatively low inter-vehicle distances while tolerating large communication delays. However, increasing the sampling frequency restricts the number of vehicles in a string. So this system helps make tradeoffs between the vehicle controller, network performance, and string stability performance criteria in the face of network-induced delays. String stability analysis also focuses on the uncertainty-like mass of the vehicle, aerodynamic drag and tire drag. A Lyapunov-based decentralized adaptive control algorithm was presented to compensate for such uncertainties in [45]. Special situations such as limited range communication and communication delay should be considered in order to ensure string stability. One case is the wireless communication is the only link with the nearest preceding vehicle, a necessary and sufficient frequency-domain condition for string stability is derived.

Different control methods are used for controlling the distance and relative speed in platoon. A PD controller is designed as higher controller and sliding model techniques are introduced in the lower controller in [49]. Vehicles equipped with WLAN communication are tested to show how the vehicles follow each other in stop and go scenario. The objective of the control system is to let the distance follow the pre-set distance and the relative speed is not considered. The desired distance is velocity dependent, which means the desired distance is changeable depending on the speed. The control method called model predictive control (MPC) can also be widely used for CACC, and from literature it appears to be more promising than PID control, because of its ability to anticipate future situations and to implement constraints directly into control algorithm. MPC applies the first input of a control sequence that optimizes a performance index calculated from predicted system behavior, based on a prediction model, subject to operational constraints, in a receding horizon approach [50]. The controller is designed to control the acceleration of the following vehicle, subject to operational constraints on acceleration. The MPC-based controller at each time step minimizes the expected errors in position and velocity and the corresponding input variation.

Besides the traditional MPC solution methods, parameterization of MPC has became more important especially when the traditional method can not supply the desired characteristics of the control system. A systematic approach of the design and tuning based on model predictive control was presented in [51]. The parameterization is a unique feature of the synthesized ACC. The system is available to tune considering the safety, comfort and fuel economy. The method is change the weights in the minimization function directly. Implementation and the performance evaluation of explicit MPC is presented in [52]. When a multi-parametric quadratic program with parameter vector is used as the cost function, the performance of the controller is available to tune depending on requirements by selecting different parameters. The tuning method still attempts to change the weights in the cost function directly. Hybrid model predictive control system [53] is used to solve a control problem for the tracking of a vehicle. The controller aims to track the velocity transmitted by the leading vehicle. The control law in this paper is divided into two phases: tracking is considered during the transient of the reference trajectory and stability is the goal after the reference reaches its steady state using the hybrid MPC in the regulation. Also, robust MPC is discussed with the presence of disturbances which are approximated by piecewise affine systems. Bageshwar *et al.* [53] developed an MPC which is used for computing the spacing-control laws for transitional maneuvers. Transitional maneuver means if there is no leading vehicle, the vehicle switches from ACC to Cruise Control (CC). The spacing-control laws based on MPC are obtained by solving the constrained optimal control problem by using a receding-horizon approach, where the desired acceleration computed at each sampling instant. Compared to the MPC based algorithm, the standard constant time gap algorithm is unable to perform the transitional maneuvers.

After the desired acceleration or velocity is generated from the higher level controller, how to let the acceleration of the vehicle follow the acceleration setpoint is another issue. Implementation of the closed-loop control of individual vehicle motions, such as steering, acceleration, and braking is defined as the lower controller. Generally, the throttle controller and brake controller are included for longitudinal control. Different throttle controllers with different control characteristic including a fixed gain Proportional-Integral-Derivative (PID) controller, a PID controller with gain scheduling, and an adaptive controller were presented in [54], [55]. All these three can yield the desired throttle distance, but the characteristics are different where the fixed PID controller is the simplest but shows oscillation in acceleration and deteriorates the riding comfort at low speed, the adaptive controller has the fastest response but is more computationally expensive. The PID controller with gain scheduling is between that of the other two controllers. A brake controller is also designed and analyzed. The desired brake line pressure can be acquired through the control system. Also, logic that dictates the switching procedure from the throttle controller to the brake controller is developed because the throttle and brake controllers are not allowed to act together at any given time. Brake system models and control laws for an Electronic-Vacuum Booster (EVB) were introduced in [56]. The model is based on a nonlinear computer model and the pressure between the vacuum chamber and the apply chamber is controlled by a solenoid-value. It is easy to find that the research on the higher level controller is more prevalent than the lower level controller. This is because even though the vehicle can not acquire the desired acceleration immediately controlled by lower controller, the higher level controller will compensate the gap between the desired acceleration and actual acceleration to make sure the vehicle has the desired dynamic motions.

B. Lateral Control

Many models and controllers have been developed by previous researchers to implement lane change and merge for automated vehicles. The basic architecture may be broken up into two layers: the strategy level and the control level. The strategy level determines when and how to make the lane change or merge by considering collision avoidance. At the control level, turning the steering wheel or pressing the throttle or brake determines how to implement the lane change or merge. The system attempts to keep the vehicle moving steadily and smoothly along the planned trajectory.

Regarding the strategy level, a model that reflects driver control strategies of lane-change behavior and planning an appropriate lane-change trajectory during the lane change process has been proposed in [57]. Different driving styles (slow and careful, sudden and aggressive) are represented by different model parameters. The maximum lateral position and arrival time can be computed using a latitudinal dynamic model. Also, an extended dynamic model can be used to emulate different lane-change strategies and to plan lane-change trajectories for collision prevention. Minimum longitudinal spacing can be calculated to prevent collision during different merging maneuvers by analyzing the kinematics of the vehicles involved in a lane change and merge maneuver shown in [58]. A general model, called Minimizing Overall Braking Induced by Lane change (MOBIL), can derive lane changing rules for both discretionary and mandatory lane change [59]. Longitudinal acceleration is used for determining the risk in terms of lane changing as well as the utility of a given lane. The safety and incentive criteria for both symmetric and asymmetric passing rules is formulated, where the incentive criterion determines if a lane change improves the individual local traffic situation, and where the safety criterion prevents critical lane changes and collisions. Four types of desired trajectories (circular trajectories, the cosine approximation to the circular trajectory, the polynomial trajectory, and the trapezoidal acceleration trajectory) involving the transition time from one lane to another lane and passenger's ride comfort were presented in [40]. The comparison indicates that the trapezoidal acceleration trajectory is the most desirable candidate for the virtual desired trajectory of a lane change maneuver.

Lane assignment that can assess the traffic situation based on the vehicle's environment and give recommendations in terms of lane changing to drivers was investigated in [60], [61]. The purpose of lane assignment is to increase highway throughput on multilane highways where there are many exit and entry points. A Bayesian Networks used for both the situation assessment and the decision making integrated with image processing for lane detection and unscented Kalman Filter for estimation and tracking was presented in [60]. For the same problem, it was formulated into a reasonably complex mathematical optimization problem focusing on the effect of lane scheduling on highway capacity as to find proper positions of partitions on an itinerary matrix in [61]. This optimal problem is solved with Genetic Algorithm. The simulation results shows that the proposed algorithm reduces travel time and increase the number of served vehicles compared to the random assignment strategy.

In the control level, there are two different approaches for lane change maneuvers [62]. One approach is treating the maneuvers as a tracking control problem and the other approach is to use the unified lateral guidance algorithm. For the tracking control approach, the virtual desired trajectory is designed considering the lateral acceleration and lateral jerk for passenger ride comfort using a sliding mode controller, which can filter tracking error. For the unified lateral guidance algorithm, the desired yaw rate generator provides the desired yaw rate along with the yaw rate track controller to achieve the desired maneuvers, including lane change maneuvers or lane following maneuvers. The steering angle commands are generated using a reference yaw rate signal and a yaw rate controller-sliding mode yaw rate controller or a robust switching controller to implement the lane change [63]. Lange change maneuvers are divided into two schemes by using roadway marker reference: infrastructure guided lane change with additional magnetic markers and automated free lane change where vehicle positions estimated from yaw rate measurement and a smooth trajectory is generated as a virtual reference path [64]. Control algorithm was designed for both of these two scenarios in [65]. Experimental results indicate that the algorithm and protocols for lane change provided accurate and reliable performance. Simulations have been conducted to validate the path planning algorithm and controller that can ensure high precision, smooth and strong robust lane change motion [66]. A linear single-track model is used to calculate the necessary inputs and all tire forces for following a desired path [67]. Then, the vehicle dynamics are integrated into the motion planning with elastic bands, thereby enhancing the drivability of the planned paths. However, this method is not exact due to assumptions such as road-tire friction coefficient, tire-loads, single-track model, and constant velocity.

Overtaking is a complex driving behavior of intelligent vehicles involving lane changing and car following. The basic process is merging out of a lane, passing a slower vehicle, and weaving back into the original lane. This process is normally broken down into three separate movements: diverting from original lane, driving in the adjacent lane, and returning to the original lane. A overtaking behavior model including lane changing behavior model and the car-following model was proposed in [68], also the coordination of the multi-controller based on the fuzzy logic controller was used for the control system. This maneuver has been extended to the platoons. Dynamic model and controller for single car-following and path-following has been extended to platoon formations on multi-lane highways. The agent-based event chain strategy was presented for forming cooperative platoon maneuvers [69]. With the development of the communication system and control system, control of multi-vehicles and multi-agent system will be implemented in the future.

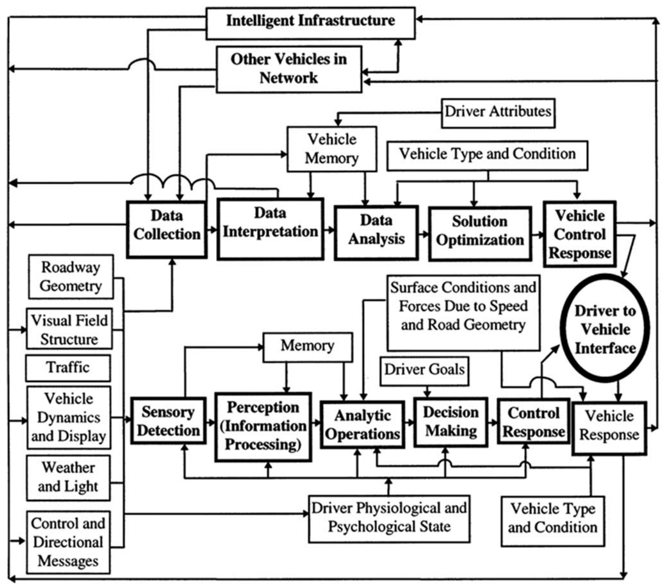

Fig. 4. Human vehicle interface with infrastructure and V2V communication (from [71]).

V. Human Factors

In most of the driver assistance system, the driver needs to maintain longitudinal or lateral control or both, permanently. Some of the tasks can be automated to certain extent by Advanced Driver Assistance Systems (ADAS). The ADAS systems normally help to relieve driver from some routine tasks; however, the drivers' supervision is required to monitor these advance assistant systems frequently and to be responsible to take the control at any time. Hence, it is important to evaluate the ADAS systems in various aspects from human-factor point of view to come up with acceptable and safe designs [70].

Since ADAS and vehicle automation are relatively new concepts, relevant literature does not comprise many detailed studies regarding the human factors issues. However, various simulation studies, involving human operator, have been conducted on partially automated systems (advanced systems, such as ACC, LDW/LKA), and even fully automated driving. Ran stressed the importance of human machine interface and presented a framework to evaluate human involvement and various concepts of feasibility and effectiveness in automated driving [71]. The relationship between the driver, the vehicle, and the infrastructure is depicted in Fig. 4.

Trimble *et al.* documented detailed literature review of key human factor studies, including the past and current advances in driver assistance systems and various level of automation, for US DOT [41]. Lervag *et al.* conducted a simulator study to investigate LDW warning systems acceptability and effectiveness [72]. Subjects experienced the system found the assistance system useful and effective in terms of improved driving behavior and traffic safety. The authors also found that user acceptance for haptic system (tactile steering wheel) is relatively high among others (tactile seat and audio/visual system). Similarly Stanley showed that the haptic modality has faster reaction time and the drivers perceived it the least annoying than both the auditory and combination modalities [73].

Griffiths and Gillespie demonstrated that adding haptic assist support sharing of control between a human operator and automation system by conducting three different experiments in which subjects completed path following and obstacle avoidance tasks using motorized steering wheel [74]. Brandt *et al.* presented similar design of the haptic human-machine interface with potential to predictive path planning algorithm [75]. Another simulation study demonstrated in [76] where haptic guidance system is developed to safely negotiate curves. In these studies, the proposed haptic-shared control solutions allowed for intuitive and continuous interaction with the assistance systems and smooth transition of control authority between human and automation.

Lerner *et al.* investigated the human factors issues in the development of Connected Vehicle (CV) driver vehicle interfaces [77]. Number of different experiments has been conducted. In experiment 1, urgency of various driving event scenarios are studied to identify the structure of user perceptions so that CV systems might be made consistent with user expectancies. In experiment 2, series of experiments have been conducted to determine and compare perceived urgency across visual, auditory, and tactile moralities within various parameters. In experiment 3, subjects' responses, during driving on a closed course, to alerts of collision avoidance system are investigated within multiple conflict scenarios. In final experiment, investigate the driver's response to imminent crash warnings when there are multiple CV products in the vehicle. The authors intended to create a basis for the design and use of safety-related warnings within the CV context is discussed. User acceptance of the lane change and merge for connected vehicles may be assumed to play an important role in the effect of automation on traffic flow efficiency. The most of the reviewed studies are generally focused on the simulation studies for lane change assistance and it's not yet clear to what extent high level of automation can be accepted by drivers.

VI. Vehicle Surroundings and Environment

A. Surrounding Vehicles

Much of the literature describes lane changing and other connected vehicle operational functions only with regard to an individual platoon. However, some literature considers how vehicles down the road stretch influence decisions, especially to have a more global approach to optimization, while some papers consider only nearby vehicles for CV operations. Note that the literature considering only nearby vehicles may only highlight the operations of a single platoon without the influence of surrounding traffic.

1) Emergency Vehicles: Vehicle surroundings and platoons on automated highways pose some interesting logistical changes, such as the operation of emergency vehicles. Toy *et al.* discuss the interesting concept of emergency vehicles in an automated highway environment [78]. The paper assumes all highways have exactly two lanes, the emergency vehicle cannot travel on the shoulder, and all vehicles are automated with platoon capability. The main premise is to assign lane changes and speed changes to vehicles so that the emergency vehicle can operate efficiently. Controls for the automated vehicles consist of a coordination layer and a link layer. The coordination layer is responsible for neighboring vehicles, while the link layer regulates traffic on a stretch of road. Different lane change maneuvers are considered, which are dubbed vortex, part-and-go, and zigzag. The vortex maneuver refers to lane change and speed change maneuvers of regular vehicles that allow an emergency vehicle to travel to its destination without disturbance. The part-and-go maneuver is used in the case that both lanes of traffic are stopped, perhaps due to a traffic accident. Inevitably, stopped traffic in its natural state will disallow movement of an emergency vehicle. The part-and-go maneuver provides a solution for this by reversing some vehicles to create stationary platoons and, ultimately, a gap for the emergency vehicle to proceed through. The zigzag maneuver is used when there is not enough space for the part-and-go maneuver. It is nearly the same as the part-and-go maneuver, except that regular vehicles must reverse even after they form the platoon.

B. Weather

Weather conditions also impact the driving environment. El Faouzi *et al.* found that, in general, rain conditions impact the time headway between vehicles in the fast lane and the speed of vehicles in other lanes [79]. Also, for roads saturated with at least 80% cars, the free flow speed decreases about 3.1% under adverse conditions. When the weather changes from dry to medium rainfall, the number of vehicles that join into a platoon is actually shown to increase by 7.5%; however, platoon speeds are reduced by about 20% [80]. Another form of adverse weather is snowfall. Heavy snowfall can reduce free flow speed by as much as 30–40% [81]. The knowledge of how rain influences driver behavior can be included in lane management tools [80]. Kim *et al.* suggest a three level strategic approach to combat weather impacts [82]. The first level is long-term strategizing which involves collecting a database of responses to certain conditions for particular areas and congestion levels. The second level is short-term planning that is necessary when extreme conditions are predicted 12–24 hours in advance. The short-term planning involves simulation to select the best response. The third level is a real-time activity that involves the collection of traffic states for the benefit of future response effectiveness. Outside the context of CV, they emphasize the importance of the short term planning via simulation given the practical weather predictions offered by meteorologists.

It is also important to consider weather impacts on platooning vehicles under various weather conditions combined with road characteristics. Lille demonstrated how past control systems fail under some weather and road conditions [83]. To do this, they simulated a two-vehicle platoon under cloudy, icy, snowy, wet, and dry conditions on a road that begins straight, becomes curvy, then inclines. Results of the simulation indicate that the platoon encountered no issues in the stable cloudy environment, but a collision did occur in the icy environment when the road transitioned from straight to curved. The lead vehicle slowed down to make the angle adjustment, and the trailing vehicle slowed down accordingly but could not do so quickly enough because of the reduced braking force due to the ice. The vehicles also collided in the inclined phase of the road under snowy conditions. To combat the insufficient technology, the authors simulate vehicle control with a new algorithm called the Natural Environment based Cooperative Adaptive Cruise Control (NECACC) algorithm with the intelligent vehicle virtual reality (IVVR) platform. The IVVR platform enables designers to design vehicle control algorithms, and simultaneously analyze and verify the model while viewing the simulation in a 3-D environment. The NECACC performance on the IVVR is superior to other algorithms in terms of balance between safety and traffic flow. Both longitudinal and lateral control were simulated and found to be successful under all the various tested natural environment conditions.

C. Road Grade

Liang showed the impact of internal forces and external forces on platoon coordination decisions, particularly the event of two trucks adjusting speeds in the catch up phase to connect into a platoon [84]. Regarding internal forces, the force produced by the engine travels through the clutch, gearbox, propeller shaft, final drive, drive shaft, and then to the wheels. External or environmental forces that act against the forward motion of a truck include air drag force, roll resistance force, and gravitational force. Newton's second law of motion indicates the following equation holds, where M is mass, a is acceleration, F_{rr} is the rolling resistance and F_{drive} is the force driving the vehicle forward.

$$M \cdot a = F_{\text{drive}} - F_{\text{brake}} - F_{\text{drag}} - F_{rr} - F_{\text{gravity}}. \quad (1)$$

Liang also constructed a table summarizing all the forces acting on a vehicle [84]. The key contributing force against the forward motion of a vehicle's is air drag, for which platooning decreases, especially for trailing vehicles. Other forces included in the table are vehicle mass, engine max torque, engine inertia, highest gear ratio, gear efficiency, final drive ratio, final drive efficiency, wheel inertia, wheel radius, roll resistance coefficient, air drag coefficient, vehicle frontal area, and air density. Neither the engine mass nor the road grade have a significant impact on coordination decisions. In fact, the only significant variable for coordination decisions is the air drag since this determines whether the fuel cost incurred in the catch-up phase will be worthwhile. The other environmental factors are negligible in the sense that the vehicles will have similar speed profiles along a road stretch regardless of the road grade and whether or not they are in coordination with another car for platooning. However, steep upward road grade has an indirect impact on the fuel use since it takes longer for vehicles to form a platoon when traveling on them.

Sahlholm developed a road grade predictive model that can be used for vehicle look ahead control [85]. The system is capable of being implemented inside a CV so that the CV can modify its speed profile accordingly to the demand of the road grade. Experiments were performed successfully and showed that the road grade estimator is accurate and supports safety, efficiency, and driver comfort. Stahl simulated the event of a vehicle using a road grade predictive model [86]. Some unaccounted error was identified in the vehicle model. Corrections to the model are proposed.

VII. Simulation and Field Testing

A. Simulation Modeling Studies

There are two main operations on the roadway: lane following and lane changing [87]. There have been numerous simulation studies regarding CACC technology, though most of the research completed focuses on lane following techniques. Lane changing is thought of as the toughest maneuver to automate. Automation of this process will increase safety by eliminating the large number of decisions drivers must make before completing a lane change movement [88]. This is a complex and dangerous task to test, thus virtual reality and simulations play an important role [68]. The current simulation studies in the literature focus on the two areas of traffic simulation and network simulation.

1) Simulation Packages: MacNeille and Miller completed a traffic simulation of the CACC technology in VISSIM [89]. The simulation uses the vehicle communications (VCOM) special programming interface to emulate a conceptual CACC device. This allows for the CACC vehicles entering the network to obtain access to navigation, V2V data and vehicle operating parameters [89]. The VISSIM network focuses on critical zones, which are areas where a small amount of maneuvers happen but there is a significant chance of congestion and vehicle safety is compromised. Examples of critical zones are intersections and highway interchanges. The VISSIM network is built in a three steps process. The first model is solely the merge zone of the highway, and the second is the merge zone along with a weave zone. Focus is given to these two zones as they are the critical zones on the highway. These zones can impede the full network if they are under-performing. The final model incorporates the merge/weave zone into a full traffic network. The results of the VISSIM model show that the flow rate of the total CACC network has a 10% greater flow than the network with complete human control.

VISSIM is not the only traffic simulator that can model CACC operations. Another popular simulator is the open source program SUMO. SUMO can be connected with other applications through its client-server architecture to allow for external control of vehicle parameters [90]. This allows for a network simulator (TraCI package) to control the leader of each platoon. The other vehicles in each platoon remain in SUMO and a module keeps their longitudinal control. The simulation results show that following vehicles obey the speed profile given to the leader externally. After the initial platoon stabilizes the platoon follows the leader at the specified spacing with negligible spacing errors. SUMO can also use the TraCI package with other network simulators such as OMNET++ [91]. VISSIM and SUMO are two of the most prominent traffic simulation packages where modeling vehicles with CACC capability. A similar framework for modeling of the technology is available in the simulators PARAMICS and CORSIM. There is a much larger number of network simulators, which are used for the modeling of lane changing, merging, and overtaking.

2) Lane Changing and Merging Simulation: Baselt *et al.* focused on the concept of fair merging, which is based on the time spent waiting for vehicles to get to the merge point in a congested scenario [92]. A conventional zipper merge is when vehicles use both lanes until the merge area where they alternate merging in zipper fashion. This zipper merge becomes fair for both lanes over time, though equal flows are not likely in practice. This is due to small deviations in unfairness on the roadway growing over time. Using vehicle to vehicle communication each car can obtain the free flow arrival time of all other vehicles in the area. Priority will then be given to the vehicles that have been waiting to merge for the longest time [92]. This merging algorithm is put into the network simulator ns-3 version 3.13. The vehicle movement model used for the simulation is the intelligent driver model (IDM). The highway mobility 2.0 framework for ns-3 is used for the highway, car, and car following models. The simulation scenario is two lanes merging into one with communications on an unreliable channel. The vehicle-to-vehicle communication is sent randomly every 1 or 2 seconds in ns-3. The algorithm is shown to increase fairness at low levels of participating vehicles.

There is still a generally small amount of research into the lane change maneuvers that are completed by vehicles in platoon. Free agent lane change is still shown in many research projects. This is when a vehicle in platoon must leave the platoon in order to change lanes then rejoin after the lane change is complete. If the members of the platoon all have the same destination there is no reason for them to leave platoon. Zhu *et al.* focused their research on road space optimization during the lane change movement [87]. This is completed by making a Negel-Schreckenberg Model or a discrete time and discrete space model for the simulation of a traffic network. The road is divided into cells, which are either empty or containing vehicle. There is then a four step process to move vehicles through the roadway: acceleration, slowing down, randomization, and vehicle motion [87]. This occurs in each time slot until the simulation is complete. During a simulation step each vehicle is either braking, or moving forward either laterally or longitudinally. There are three types of lane change investigated: tail to head, head to tail, and random. An algorithm is created for each type of lane change maneuver. Tail to head lane change gives the highest positive results through simulation. As this is a fully theoretical work it will be necessary to create an algorithm for practical applications such as traffic simulation.

The relative position of merging along with the control of motion including acceleration, velocity, and safety is a subject of research. This led to the concept of mild merging, where the acceleration of relevant vehicles is restricted so comfort and limitations of accelerations are considered. This allows for the merging path to be optimized, and the vehicles will be kept in the center line of lanes making movements safer for all drivers. The optimization process relates the lateral motion of merging to its longitudinal motion [93]. This is done on a personal computer using the C/GMRES optimization method. The outputs from the simulation can then be used to control vehicles in simulation directly. The optimized merging path outputs from simulation are reasonable when compared to real-world merging success.

Hsu and Liu investigated three possible platoon lane change (PLC) movements: leader, predecessor-I and predecessor-II. PLC leader allows for all the vehicles in the platoon to complete the lane change simultaneously [42]. During the leader PLC movement there is no communication delay between the platoon vehicles. This is not the case for either of the predecessor platoon lane change movements. In PLC predecessor-I the lead vehicle notifies each follower vehicle to begin the lane change maneuver one by one with a communication delay. The vehicles in predecessor-I are separated by a distance that is equal to or less than the MSS. The situations where vehicles are separated by a value smaller than the MSS are deliberate. The MSS is the vehicle speed multiplied by the communication time. If the vehicles are separated by a distance larger than the MSS then the PLC type must be predecessor-II. This has the same procedure except for an added step at the beginning of the maneuver of decreasing the vehicle separation to MSS. Also, at the end of the maneuver increasing the separation from the MSS back to the original spacing. Each of the three procedures were simulated using SmartAHS, which is a library of shift language that provides discrete and continuous control for AHS [42]. The simulation has four vehicles in platoon change lanes on a straight section of roadway. PLC leader performs the best of the three as there is no communication delay in the maneuver. PLC predecessor-I has the same result with the addition of communication delay, which is 0.02 seconds per vehicle. Lastly, PLC predecessor-II has significantly larger time to complete the maneuver, as the original spacing has to be taken into account. For the simulation done by [42], the results for leader, predecessor-I and predecessor-II are 5 s, 5.06 s, and 7.85 s respectively. These times are for completion of the lane change maneuver. Turan *et al.* presented a combined lateral and longitudinal rule based upper level control algorithm for a cooperative vehicle [94]. The system applies a two level hierarchy control where the upper level controller does the decision making by using a finite state machine and the lower level controller implements speed and steering control. A nonlinear single track model and Dugoff tire model are used in the MATLAB/Simulink model. A detailed flow chart of lane change algorithm is given describing the decision making process. CACC capable vehicles are considered in three different simulation scenarios: highway following, joining platoons and lane changing platoons. Simulations combining ACC car following, merging/lane changing control with inter-vehicular-communication (IVC) in [95] show that the aid of IVCs eases both the requirement on the on-board processing and reduces the delay time, which ensure the controllability on vehicles.

B. Field Testing

Highlighting how quickly platooning is transitioning into commercial practice; many field tests have been performed on platoons. The fact that platooning has been done in experiments already is encouraging to researchers; it indicates that in many ways we have already arrived to the future of road travel, and it is just a matter of time before platooning is a standard mode of transportation. In general, field tests are typically run to validate simulation results, to show that a new technology actually works in practice [96], to collect data to see what platooning metrics result such as fuel savings [97]–[99] or to try platooning under non-theoretical conditions such as mixed traffic [100]–[102].

1) Lane Change and Merging Testing: There have also been a number of successful field tests performed related to CACC lane change and merge. [103] performed field tests with their vehicle overtaking detection system. Sivaraman *et al.* presented an implementation of driver assistance of merging maneuvers [104]. The vehicle's surrounding is monitored via multiple sensors (cameras, radars, and LIDAR). The measurements from sensors are integrated into a representation called Dynamic Probabilistic Drivability Map (DPDM) where this DPDM acts as a compact representation of the surroundings. The system is able to give recommendation of safe merge maneuver to the driver with appropriate acceleration or deceleration. Ozguner *et al.* and Rajamani *et al.* performed one of the first experiments involving lateral movement [65], [105]. Dao performed experiments with two cars to test his work on lane positioning [106]. The lane positioning technology enables the cars to identify which lane they were in and whether they were in the center of their respective lanes. Experiments were conducted for high speeds, low speeds, two lanes, and three lanes. Milanes *et al.* ran a field test with four equipped cars [107]. The first experiment was performed by simply adjusting the vehicle gap between two of the cars. The second experiment was set up with the cars in platoon. A vehicle that was not equipped with any communication technology changed lanes into the platoon, then quickly changed lanes out of the platoon as in a highway entry or exit scenario. Milanes *et al.* conducted experiments with roadway merging [108]. In particular, a connected vehicle automatically merged from a minor roadway onto a congested major roadway; that is, the speed of the merging vehicle and the speeds of two vehicles on the major roadway were adjusted automatically to enable smooth merging. Elm described an experiment in which two vehicles swapped positions by lane change and merge; however, the lateral controls were manual [109]. Milanes *et al.* conducted a field test with manual lateral control in two cyber cars traveling at low speed to enact driving in an urban environment [107]. Marouf *et al.* conducted a field test with a three car demonstration [44]. The idea for this paper is that of automated parallel parking combined with a platooning. A lead car with a driver travels to a parking space in which an empty connected vehicle is parallel parked. The connected vehicle reads that it should move from its parked position to the parallel position directly adjacent to it by maneuvering out of the parking spot. The empty vehicle then joins the leader vehicle and follows it in platoon to whatever new parking spot and automatically parallel parks there.

VIII. Conclusion

This survey has presented the current state-of-the-art of platoon merging/lane change control algorithms, as well as supporting relative positioning technologies, communication standards, simulation tools for concept evaluation, and considerations of vehicle surroundings. For platoon lane change control vehicle modeling, controller architectures, and specific control algorithms are presented that will allow for the augmentation of CACC control algorithms to allow lane change and merging. Current sensor packages of CACC capable vehicles are discussed as well as new algorithms for DGPS, computer vision, and sensor fusion. These algorithms provide accurate state feedback information to be used in control algorithms. DSRC communication architecture has been outlined along with networking techniques that can be used to extend the horizon of communication beyond the actual range of individual receivers. Simulation tools have been discussed that allow the testing and impact evaluation of various merging and lane change controllers. Finally, vehicle surroundings and their impact on vehicle dynamics and control are presented.

Current state-of-the-art technologies lend themselves well to CACC platoon merging. Extensive work has been conducted in the areas of modeling and control of lane change maneuvers. Many of these algorithms have been shown to work in real life situations. Positioning technologies are perhaps the most advanced section within the scope of this literature review. Precise knowledge of the host vehicles position relative to other vehicles is required for many systems currently available on production vehicles such as: lane departure warning, blind spot detection, adaptive cruise control, and parking assist systems. However, little research was found which allows vehicles capable of CACC to share this sensor information with vehicles in close proximity to provide a more robust picture of a platoon's surroundings. These types of data fusion require reliable communication vehicles. The primary weakness of current DSRC protocols is the lack of standardization of merging messages and also the lack of any appreciable market penetration. From the traffic simulation studies it is evident that there are traffic simulation packages are available that will allow for connected vehicles to be modeled. Using a traffic simulator and its corresponding package to allow for network simulation will allow for the most beneficial simulations moving forward. An example of this framework is the traffic simulator SUMO and its network simulation tool TraCI. Mild merging and PLC maneuvers are two techniques that have been shown in the literature to improve traffic flow. These techniques have not yet been implemented in a conventional traffic simulator and would allow for a greater understanding. Vehicle surroundings research shows particular strength in managed lane behavior as well as modeling of the effect of harsh weather on platoons. It is the general finding of this literature review that more extensive field testing of simulated concepts is required to validate the theories presented in the research.

There are several areas revealed from this literature review that require special attention in order to move toward implementing CACC systems capable of lane change maneuvers. Particular areas of concern become apparent when contemplating the roll out of these systems. The limited market penetration of V2V and V2I systems complicates the merging/lane change maneuvers. However, it is of limited use for external systems without communication with the merging vehicle due to their reliance on on-board sensor data from the merging vehicle. Without research in this area, the CACC platoon would be incapable of gap creation for the merging vehicle without V2V communication. The system would merely react to what it would view as a "cut-in" situation leading to sub-optimal performance of the platoon following distance. On the other side of the scale with respect to DSRC communication, little experimental research has been done considering congestion on the DSRC frequency. As systems are introduced that rely heavily on these communications, it becomes increasingly important that experimental data be collected in congested areas. The final area of research suggested is the design and experimental validation of steering assisting systems such as "drive-by-wire." This will be the final step in moving from simple longitudinal CACC systems to platoons capable of lane change and merge maneuvers.

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