Research Advances in Intelligent Collision Avoidance and Adaptive Cruise Control

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***Abstract*—This paper looks into recent developments and research trends in collision avoidance/warning systems and automation of vehicle longitudinal/lateral control tasks. It is an attempt to provide a bigger picture of the very diverse, detailed and highly multidisciplinary research in this area. Based on diversely selected research, this paper explains the initiatives for automation in different levels of transportation system with a specific emphasis on the vehicle-level automation. Human factor studies and legal issues are analyzed as well as control algorithms. Drivers' comfort and well being, increased safety, and increased highway capacity are among the most important initiatives counted for automation. However, sometimes these are contradictory requirements. Relying on an analytical survey of the published research, we will try to provide a more clear understanding of the impact of automation/warning systems on each of the above-mentioned factors. The discussion of sensory issues requires a dedicated paper due to its broad range and is not addressed in this paper.**

***Index Terms*—Adaptive cruise control (ACC), collision avoidance, collision warning.**

I. INTRODUCTION

VEHICLE and highway automation is believed to reduce the risk of accidents, improve safety, increase capacity, reduce fuel consumption and enhance overall comfort and performance for drivers. There has been enough reason to assume that more automated automobiles relieve the driver from many undesirable routines of driving task. It has also been known that many of the car accidents are due to human errors. Therefore, the conclusion has been that with a robust automated system the chance of car accidents can be reduced. With the overwhelming increase in the number of vehicles on the road another concern has been road capacity. Some kind of automation that would help to safely increase traffic flow has been considered as one potential solution to congested highways. A smoother cruise with an automated system can reduce fuel consumption and engine wear.

Based on all these potential benefits of automation, research on automating some or all aspects of driving task has been going on for decades now [1]. However, there were limits in practical implementation of such systems due to rudimentary electronics and sensor technology.

While the history of automation goes back to 1930s, in the late 1980s and beginning of 1990s, state and private funded programs started more focused research in the United States, Europe, and Japan [2], to bring the idea of automated or intelligent transportation systems closer to reality. The main initiative was to improve highway capacity and safety with automation in highway and vehicle level [3]. The very well organized, thorough and sometimes futuristic research in this era, along with the rapid advances in electronics and sensor technology, contributed to a more vivid understanding of the difficulties and potentials of such systems. Although the research in this period was focused on advanced highways it was a good basis when later on the interests switched from advanced highway systems (AHS) to intelligent vehicle initiative (IVI).

Now in the beginning of the 21st century while some automakers have already introduced features like adaptive cruise control (ACC) in their top of the line cars, many others are pursuing research to introduce ACC and other advanced features like collision warning and avoidance systems into their products. The evident trends of development pictures more comfortable and safer driving scenarios in the near future and what once looked very futuristic now seems within a few years reach. However, there are still many issues that need to be addressed before driving assistance systems can be widely introduced in the future cars. The theoretical and experimental research on control issues is in a well-developed stage. The sensory problems pose stronger challenges on the development of driver assist systems. While today's technology has addressed many of the sensory issues, many still remain to be solved. Moreover the impact of automation on the driver necessitates a very fundamental understanding of human factors in relation with the automated or semi-automated driving controls or assists. Research on the human factor side has not been little but the importance of this issue demands a lot more work. Legal and institutional aspects of automated cars are also a very important concern.

While a lot has been said about improved safety, increased highway capacity or higher comfort level with automation in different papers, sometimes inconsistencies exist between different points of views on these matters.

This paper looks into the current research underway in certain areas of vehicle automation and their impact on comfort, safety and highway capacity. ACC, collision avoidance and collision warning systems (CWS) are the main focus of the paper. Also the research on advanced highways is briefly reviewed as it is closely related to the above-mentioned subjects. Control algorithms and technology, human factors, legal and institutional

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issues are briefly reviewed with the main goal of providing a coherent account of what has been done, rather than critiquing individual papers. At the end of each section we present analysis and conclusions based on the works reviewed in that section. The paper should serve as an introduction for those who are less familiar with this subject. The analysis of the multidisciplinary issues should provide useful perspectives for researchers who are involved in a particular related field. While it is not possible to cover the large number of publications in this area, the key findings and trends of research are included. The focus is on more recent literature since good reviews already exist on the relatively long history of the subject [1], [4], [5]. We do not address the issues related to sensory requirements in this paper as it is a vast area and requires a dedicated paper that investigates them.

II. From Automated Highway Systems to IVI

The research tendency in the early 1990s in the United States and Europe was more toward AHS which required measures in both infrastructure and vehicle level. In Europe, the major research was under PROMETHEUS program funded by European automakers and governments of the European Union. In the United States, the PATH program founded by California Department of Transportation and Institute of Transportation Studies of the University of California at Berkeley sponsored major fundamental research projects in advanced vehicle and highway systems. The research at PATH further stimulated research initiatives on advanced concepts in transportation across the United States. Similar research interests were followed in Japan as well [1]. The idea was to substitute a group of man-made driving decisions and actions with more systematic and precise machine tasks to achieve regulated traffic flow and, therefore, reach safer highways with higher capacities. Detailed studies were carried out on automating many operations that take place on a highway. A thorough picture of the operations that can be automated on the future advanced highways and the relationship between such functions were presented in some very informative papers [6] and [7]. In these papers, different layers were proposed for different levels of automation and a detailed account of the operations belonging to each layer was explained explicitly. For example in a lane change maneuver, a central planning layer is responsible for coordinating a safe and timely maneuver with other vehicles on the highway and commanding the appropriate move. A local regulating layer of each vehicle performs the necessary operations to fulfill such a command. While automation to the extent specified in these papers is futuristic from practical point of view and requires new elements in the infrastructure as well as all participating vehicles, the distinct definition of each operation and its related issues, helps advance the state-of-the-art in partial automation. Such an outlook paves the path to the long-term goal of advanced highways and is also beneficial for short term applications.

In the same framework considerable research has been carried out in control and sensory requirements for platoons of vehicles. The idea is to form a queue of vehicles that follow each other very closely at highway speeds without the risk of crashes or interfering with other platoons of vehicles. It is shown that with shorter spacing between vehicles, highway capacity can be considerably improved [8] and [9]. However, a constant spacing platoon is stable only if certain types of vehicle-to-vehicle communication are available [10]. This requires that all the vehicles in a platoon be equipped with some sort of radio communication devices. Experimental platoon tests on highways have proved successful [11] and [12] and research on platoons and automated highway systems is being continued to support the next generation highways. On the other hand due to financial and practical limitations, the short-term tendency has switched from AHS to IVI to emphasize more on driver assist systems that can independently be implemented in today's generation of cars without the costly modifications in the infrastructure. Such assist systems provide the driver with information, warning and operational support. ACC, stop and go cruise, collision warning and collision avoidance systems are being developed in this context. Many findings of the automated highway research are directly applicable in these fields too, as many control and sensory requirements are similar. However, there are major differences in the philosophy behind each system since the impact of each on safety, road capacity and driving comfort could be different.

An enhancement to the cruise control feature of today's car is ACC systems, which can detect the leading vehicle and maintain a specified spacing between the two vehicles [13]. The goal is to relieve the driver from the routine of spacing adjustments at cruise speeds on highways. And therefore it is marketed as a mean for driver's comfort. As a potential feature that can enhance the marketability of their products, major automakers are conducting extensive research in developing robust ACC systems and some carmakers have already equipped their luxury cars with the ACC feature [14]. However, it remains an open question whether this feature can also result in safer traffic patterns or how the impact of it is on traffic flow. Stop and go cruise control is an extension to ACC which is able to automatically accelerate and decelerate the vehicle in city traffic [15] and [16]. Stop and go control is meant to reduce driver workload in suburban areas where ACC systems are practically ineffective. Due to the more complex driving environment and more stringent sensory requirements in lower speeds, the challenges in developing stop and go systems are more than ACC systems.

While development in crashworthiness has led to car designs that are much safer in the event of a collision, they cannot reduce the chances of a collision. Worldwide statistics shows a decreasing trend in number of fatalities in car accidents through the years but an increased number of accidents. Car accidents still occur everyday, the minor ones cause major economical losses to the society, and more serious ones result in injuries or loss of lives. Rear-end collisions, for example, account for approximately 1.8 million crashes annually which is 28 percent of all crashes. In 1998, rear-end collisions, resulted in 855 000 injuries and 1570 fatalities [17]. More strict traffic regulations and safety standards can be helpful in preventing the accidents to a certain degree, but as the driver is limited in recognizing, judging and operating in hazardous situations, accidents are practically inevitable. However, many of this type of accidents can be avoided if the human driver limits can be overcome by automating some parts of the driving tasks, this time with safety initiatives. This initiative has encouraged extensive research in collision warning and collision avoidance systems that can improve passenger safety and reduce losses by preventing the accidents that occur beyond the control of human driver [18], [19]. Many of the components of such systems are similar to those studied under AHS. The major difference is the different philosophies behind each.

The CWS can warn the driver of an imminent collision. Statistical accident data show that a considerable portion of accidents is caused by driver's delay in recognizing or judging the "dangerous" situation. In forward collisions for example, it is claimed that if an extra half a second of warning time is provided to a driver, 60% of collisions can be avoided and with one second of warning time this portion increases to 90% [20]. Therefore it is believed that providing some sort of appropriate warning to the driver can help reduce the probability and severity of car accidents. Car companies are involved in major research plans to implement CWS, which can increase safety and therefore marketability of their products [21]. Major regulatory state agencies are also interested in this area to improve safety of the roads. CWS have been in practical use in commercial heavy-truck fleets [20] and buses [22] in the United States for a few years now and have shown very successful. However, with all the known benefits of such CWS, the carmakers bear the liability of their product and this slows the process of introducing CWS in passenger cars. Also technical problems like issuing false warnings need to be resolved before CWS can gain consumer confidence. A more futuristic measure to prevent collisions is a collision avoidance system that can perceive the dangerous situation and automatically control the vehicle out of danger. When the driver fails to perform the necessary emergency maneuver, a collision avoidance system will take the control and brakes and/or steers the car to avoid a collision. The control paradigms that can perform slight emergency maneuvers are in an acceptably developed stage. However, more robust situation-recognition systems are required before such systems can find practical use in every vehicle. Very robust and reliable sensory system is essential for reliable operation of the system. Liability issues are even more important for collision avoidance systems as they can potentially overrun driver's decision and result in some unforeseen scenarios. Therefore liability issues are stronger challenges than technical barriers.

In the following sections, control issues, human factor concerns and liability considerations are discussed in more detail in separate sections. Sensory requirements need a dedicated publication and are not discussed in this paper.

III. Vehicle Control Schemes for Automation

Perhaps the most researched area in driving automation is the control methodology. Once sufficient information is gathered to understand the state of the vehicle with respect to other vehicles and the road, a control scheme is required to either assist the driver in controlling the vehicle or autonomously control the vehicle itself. Normally, a higher-level controller determines the required kinematics of the vehicle for fulfilling requirements and meeting the constraints. In driver assist systems this required kinematics would be compared with the driver's performance and appropriate warning is provided to the driver if necessary. In "more" automated systems, the higher level controller determines the "desired" motion of the vehicle for lower level controllers which control the engine, brakes, steering, etc. Therefore design of the higher-level controller requires a good understanding of the vehicle environment. Design of the lower level controllers, on the other hand, requires a good model of the vehicle itself. There has been considerable theoretical and experimental research on developing controllers and models of different levels of complexity.

A. Supervisory Controller

The majority of studies have focused on longitudinal control of vehicles, which is the base for different automated car initiatives like car platooning, ACC and forward collision warning and avoidance systems. While lower level controllers are very similar for all these different control initiatives, the differences in control design philosophy are reflected more in the higher-level controller. Raza and Ioannou [23] and [24] have presented a well-structured high-level (supervisory) control design for vehicle longitudinal control in different modes of operation. This supervisory controller processes the inputs from the driver, the infrastructure, other vehicles, and the onboard sensors and sends the appropriate commands to the brake and throttle control.

ACC and platooning are both vehicle-following modes with some similar issues. However, in car platoons the goal is to maintain very close following spaces between the vehicles to increase highway capacity while in ACC the main objective is maintaining a safe distance to relieve the driver from spacing adjustments. These objectives are reflected in the supervisory controller design. In a platoon the acceleration of the vehicle is determined to ensure string stability of the vehicles that are closely following each other, such that vehicle-to-vehicle spacing error does not grow toward the end of the platoon [8]–[10]. It is shown that vehicle-to-vehicle communication [1], [9], [10] or use of rear-end sensors [25] is necessary for guaranteed string stability of a platoon. This need for vehicle-to-vehicle communication restricts practical and widespread implementation of platooning for passenger vehicles. More recently the interest has been more on fleets of heavy duty vehicles (HDV). In [26] a design for truck platoon control is explained and experimented. The emphasis on HDV platooning has been more for increased safety and efficiency of the fleet rather than increased highway capacity. That could be reflected in a less aggressive supervisory controller for trucks. Also communication for trucks of a commercial fleet is more easily implementable than for random passenger vehicles on the road. However, there are issues in the design of the supervisory controller that are unique to heavy vehicles. Mass of the heavy duty vehicle can vary considerably in different loading scenarios and mild road grades can be serious loadings for a heavy vehicle [27]. Good estimation of mass and road grade can improve the performance of the supervisory controller by reducing the chance of issuing infeasible control commands [27], [28].

For ACC, the emphasis is on safely increasing driving comfort rather than increasing road capacity. Therefore normally a constant headway policy or other safe following policies is used to determine the following distance. The proper spacing is mostly determined by human factor issues which will be discussed later in this paper. Once the desired spacing or velocity is determined, the upper level controller calculates the desired acceleration that "smoothly" and "quickly" reduces or increases the spacing or velocity to their desired values. To imitate human following behavior fuzzy or neurocontrollers can be trained for spacing adjustments as suggested in [29]–[31]. However, many proposed supervisory controllers are based on mathematical models rather than real human behavior. Examples are application of nonlinear control schemes like sliding mode control [32] and optimal dynamic back-stepping control [33] in deriving the desired acceleration on the supervisory level. Liang and Peng [34] and [35] have implemented an optimal control design to balance between various requirements in a following maneuver. The question is whether a human-like following behavior is the best possible following way. It is true that an ACC which is trained by real-driver data might feel more "natural" but we need to also consider that different drivers have different following habits and it is hard to please the wide spectrum of drivers with a system that imitates a selected group. Besides a human driver makes decision based on limited sensory tools. Imitation of this behavior while using more accurate electronic sensors may not necessarily be optimal. Moreover a mathematical following rule can be more transparent than black-box human-like following scheme.

The global impact of ACC on safety of highways is studied by Touran *et al.* [36]. They have used Monte Carlo simulations to evaluate the probability of collision for a string of vehicles. Their conclusion is that ACC significantly reduces the probability of collision between the ACC controlled vehicle and the leading vehicle. However, it slightly increases the chance of collision for the followers of the equipped car.

The impact of ACC on traffic flow is a secondary effect and is dependent on spacing policy which is determined at the supervisory level. Liang and Peng [37] have studied the influence of ACC equipped vehicles on the string stability of a queue of manual and ACC controlled vehicles. They have shown that if properly designed, ACC equipped vehicles can help improve the average velocity of the mixed traffic and also reduce the average acceleration levels. These improvements translate to higher traffic flow rate, lower fuel consumption and smoother and safer rides. Bose and Ioannou [38] show up to 60 percent reduction in air pollution if 10 percent of vehicles are equipped with ACC. They argue that smooth response of ACC vehicles designed for human factor considerations filters out traffic disturbances and therefore reduces air pollution and fuel consumption.

The driver initiates the ACC mode and is responsible for monitoring the performance of the system. Collision avoidance (CA) and collision warning (CW) systems on the other hand are active during the driving course. CA/CW are responsible for monitoring the driver behavior and for taking appropriate action if necessary. This basic functional difference between CA/CW and other longitudinal control initiatives increases the importance of human factor concerns in designing a robust higher-level supervisory system which is safe and effective. The ergonomics of the problem will be discussed in more detail later in this paper.

The short-term collision avoidance/warning research tendency has been more toward longitudinal control (emergency braking) or warning to avoid rear-end collisions. In general when the distance from the preceding vehicle becomes smaller than a warning distance, warnings are given to the driver. In a more critical situation the braking distant measure is used to automatically brake the vehicle. The appropriate warning and braking distance are the key design parameters and are determined based on models of different complexity such as the models developed by Honda and Mazda [39]. Wilson [40] derived envelopes for determining brake timing for rear-end collision warning. A good model should also take into account the conditions of the road and the driver. A sensor or model based method is necessary to determine the tire-road friction. Yi *et al.* [41], [42] have derived a tire-road friction model for the design of a CA/CW system. Seiler *et al.* [39] have proposed modified versions of Honda and Mazda algorithms, which use tire-road friction estimation to scale the critical distances. Also provisions were made for the driver to be able to scale the warning and braking distances according to his/her preference.

The lateral control of vehicles for lane keeping, coordinated lane changing or emergency collision avoidance maneuvers is a more complex control task as it happens in a more complex two-dimensional environment. Lane keeping driver assist systems can be commercialized in the near future. The research toward automating lateral maneuvers has a longer-term goal when such systems are robust enough to be deployed without safety risks. Kinematics of a lateral maneuver is determined by the supervisory controller [43], [44]. Jula *et al.* [45] have studied the kinematics of a lane change maneuver and the conditions under which lane changing/merging crashes can be avoided. Their results are useful in assessing the safety of a lane change maneuver and in designing CA/CW systems for them. Eskandarian and Thiriez [46] have proposed and designed a neural network to determine the path of the vehicle in a collision avoidance maneuver based on a purely learning scheme. While each of the proposed schemes have strengths and some have proved successful in experimental conditions [43], the complexity of a real scenario requires logical checks and redundancy in the algorithms to avoid unforeseen circumstances.

B. Vehicle-Level Controllers

While in designing the higher-level controller only the kinematics of the vehicle is important, the design of the vehicle level controllers requires a good model of dynamics of the vehicle. For longitudinal control a model for the engine, the drivetrain, the tires and the brake system is required. For lateral control a steering model is also necessary. Realistic models of these vehicle components are basically highly nonlinear. A few different methods have been proposed for designing appropriate controllers.

Engine torque is a nonlinear function of many parameters. Static engine torque maps which are used in most of control designs are again nonlinear functions of engine speed and throttle angle. Swaroop *et al.* [10] have used Input/Output linearization to handle the nonlinearities of the engine. Gerdes and Hedrick [32] have designed sliding controllers for similar engine and brake models and have shown successful tracking of desired kinematics in simulation and experiments. A more simplified longitudinal model of the vehicle is presented in [25]. Details of the engine control design can be found in [47]. A comparison of different engine models for vehicle longitudinal control is presented in [48]. Schiehlen and Fritz [49] have proposed and compared a few different linear and nonlinear controllers for engine control. Mayr [50] has skipped modeling of the engine and driveline and has instead introduced a simplified longitudinal model, which relates the tire force to the throttle angle and vehicle's speed. He has designed a longitudinal controller based on this model.

Another challenge in longitudinal control is modeling and control of the brakes. The performance of the brakes depends on various parameters, like the brake temperature and tire-road friction which are not constant and are difficult to model. An example of a nonlinear brake model can be found in [51]. Feedback linearization is used for this brake model for controller design and good performance is shown in experiments. Yi *et al.* [41] and Yi and Chung [42] used a sliding mode controller to control a nonlinear brake model for CW/CA applications. In heavy-vehicles another braking mechanism which is suitable for ACC applications is engine-braking. In a diesel engine, when engine-braking or compression-braking is activated, fuel injection is inhibited and as a result the turbo-charged diesel engine turns into a compressor that absorbs energy from the crankshaft. It is an effective and economical way for slowing down a heavy vehicle and is suitable for longitudinal control of HDVs for speed adjustments. However, the nonlinearities of the engine are present in the compression braking too and static maps for compression braking could be used to calculate the retarding torque. In [52]–[54], Druzhinina *et al.* present different compression brake control designs for longitudinal control of heavy trucks. Experimental results on successful coordinated use of service brakes and compression braking in longitudinal control is presented in [55].

Most of the above mentioned controllers are fixed gain controllers. However, vehicle parameters vary during the life time of the vehicle. Certain vehicle or road parameters, like rolling resistance, could change during a single trip. The issue of sensitivity to parameter variations is especially important for heavy vehicles. The mass of a heavy duty vehicle can vary as much as 400% from one trip to the other. Road grade is also an influential parameter on the performance of HDV. The closed loop experiments performed by Yanakiev *et al.* [56] indicate that the longitudinal controllers with fixed gains have limited capability in handling large parameter variations of an HDV. Therefore it is necessary to use an adaptive control approach with an implicit or explicit online estimation scheme for better control performance. Examples of adaptive controllers for vehicle control applications can be found in the work by Liubakka *et al.* [57], Ioannou *et al.* [58], Oda *et al.* [59]. For longitudinal control of HDV, Yanakiev *et al.* [60], [61] have proposed an adaptive controller with direct adaptation of PIQ controller gains. Druzhinina *et al.* [54] have designed an adaptive control for HDVs using a Lyapunov function approach. Youcef-Toumi *et al.* [62] have proposed the time-delay control method for longitudinal control of the vehicle. The time delay controller uses past observation of the systems response and the control input to directly modify the control action rather than adjusting the controller gains or identifying the system parameters.

For lane keeping or emergency lateral maneuvers for collision avoidance, steering control is necessary. Modeling vehicle steering depends on tire-road interaction which is dependent on many parameters and is therefore complex. Most papers assume simplified models for steering control design. Shimakage *et al.* [63] have developed a steering torque control system for driver assistance in lane keeping. They proposed an LQ control design for a bicycle model of the vehicle and tested it successfully on actual vehicles. Peng and Tomizuka [64] have developed a more detailed steering model for a four-wheel vehicle model and have designed a preview steering controller for path following. They have shown improved tracking results when preview information of the road ahead is available. Chan and Tan [65] propose a post-crash steering control to stabilize the trajectories of the vehicles involved in a collision.

The major effort in the above-mentioned control designs is spent in developing good models of engine, transmission, service brakes and steering. As far as research in these areas is concerned, much of the information about the vehicle components like engine and transmission unit is proprietary and therefore academic researchers have limited access to this information. However, in today's vehicles a lot of information is available through the engine control unit interface. Signals like static engine torque, transmission status, engine speed, vehicle speed which are communicated between different controllers on the vehicle can be accessed through the vehicle's CANBUS. These signals are transferred under certain standards which are open to the public. For heavy vehicles for example, the J1939 standard recommended by Society of Automotive Engineers (SAE) is the practiced standard [66]. The CANBUS information can be recorded real-time in road experiments and translated using the corresponding standard. The data could then be used to construct or validate models for engine, transmission and service brakes. This experimental data could even be used for direct design of controllers [67].

In developing vehicle models for longitudinal control, it is mostly assumed that tires do not slip. This assumption reduces the complexity of the models and the controllers. This assumption is acceptable for applications like ACC where high acceleration or decelerations are unlikely. However, in an emergency braking maneuver for example, the wheels will slip. In such a scenario a good tire slip model is necessary for good performance of the controller. While this issue has been considered in some research papers, more research in the modeling side is required in the future. Tire-road interaction in different scenarios is also important for lateral control designs. This information would be crucial to a collision avoidance system that should safely steer the vehicle away from danger.

This given summary of the state-of-the-art of vehicle control systems represents only an overview of the extensive research conducted in this area. The control methodologies are in a well-developed stage and are capable of fulfilling many of the short-term objectives of IVI, particularly ACC. However, for collision avoidance where more aggressive control actions are necessary more research on developing models of the components and control design is required for guaranteed safety.

The more challenging problems of automation emerge when the impact of such automation on the drivers of the involved vehicles is being considered. Section IV elaborates more on the human factor side of automation.

IV. Human Factor Issues

The automated driver functions and assist systems are no longer prototypes and in the next few years many production vehicles will be equipped with such systems. Goodrich and Boer [68] categorize driver assist systems into driver assist systems that are initiated by the driver to safely promote comfort and assist systems which are initiated by the system to comfortably promote safety. Human-factor studies play the key role to the successful implementation of both types.

With the advanced automated driving assist functions, the driver is responsible for supervision of the automated task to ensure safe and satisfactory performance of the system. The assist systems normally relieve the driver from some routine physical tasks in driving, for instance in maintaining a steady headway from the preceding vehicle, but they increase driver's supervisory responsibilities. The tradeoff between the relief and added pressure needs to be evaluated from human-factor point of view to come up with acceptable and safe designs for the assist systems.

Designing a collision avoidance mechanism is even more complicated as it is now the system that is responsible for monitoring certain driver's actions or consequences of such actions and to identify if a collision avoidance maneuver is necessary. A collision warning system has the added responsibility of communicating the situation to the driver so the driver can take a timely and safe evasive action. A poorly designed and overly sensitive system can increase driver's workload, which as a result can decrease driver's situation awareness, comfort, and even safety. A very good understanding of the driver's psychology and behavioral habits is therefore essential.

Human factor issues have recently been the subject of substantial research both in government agencies and industry. Numerous projects are defined under the IVI program of US DOT to determine the important human factor issues in deployment of driver assist systems. A compendium of projects dealing with human factor issues in IVI can be found in [69]. In December of 1997, an IVI human factors technology workshop was held in Troy, Michigan. In this workshop, experts and stakeholders from public and private sectors and academia were asked to provide inputs to help identify important human factor issues [70]. During two days of the workshop many research statements were developed which can be categorized in four main categories of human factor research needs: 1) Identifying the IVI implications for the driver-vehicle interface 2) Developing driver models for IVI 3) Providing industry with human factor design guidelines and standards for IVI 4) Determining the feasibility and optimum design for integration of IVI systems. A more detailed description of finding of this workshop can be found in [70]. Also a forum was held in 1997 by ITS America in San Diego for various industry stakeholders to voice their opinions and comments about IVI. Human factor issues were among the major concerns in the forum conclusions. There has also been a joint international initiative for evaluating the safety impact of driver assist systems, including related HF issues [71].

The research directions should determine the baseline human driver behavior and then evaluate how different designs affect driver's workload and how safety is influenced. Consequently designs can be improved to achieve better driver acceptance and increased safety. An example is the published research results on ACC designs from a human factor perspective.

Some field studies have focused on determining driver car-following behavior [72]–[75] and on identifying different driving states [76]. These studies determine the baseline human-driver behavior and help designing ACC systems that are compatible with human driver tendencies.

To access driver acceptance of ACC, Hoedemaeker [77] have conducted a questionnaire study and two driving simulator studies. They found while shorter headway times increase the traffic flow, close following distances can be stressful for some drivers and thus concludes that an adjustable headway is necessary to meet interests of different drivers. In some rural road driving scenarios, like passing other cars, it was observed that ACC could be more dangerous than helpful. To avoid such problems the drivers need to understand the limits of ACC and learn to disengage the system when required. Based on result of their research they conclude that a well-designed ACC system can improve the driving comfort and also harmonize the traffic flow as it reduces speed variations.

In another simulator study Stanton *et al.* [78] studied driver workload and reclaiming control with ACC. They observed reduced mental workload when ACC is engaged, as the driver is relieved from some of the decision-making elements of the driving task. But they considered the possibility that lower levels of workload may indicate the extent to which the driver was out of the vehicle control loop. Similar to other human supervisory tasks, reduced levels of attention associated with lower levels of workload may affect the ability of the driver to maintain awareness of status of the system. They believe that inter-vehicle spacing for ACC mode should be larger than the manual mode to provide the drivers with enough time to reclaim the control of the vehicle in an emergency scenario. They also suggest that more attention is required on the driver interface of the ACC system to help keep the drivers in the control loop. Such an interface would help the driver to develop appropriate internal mental representations that will enable him to understand the limitations [79].

In the same direction Goodrich *et al.* [80] emphasize that safe and effective ACC design requires that the operational limits of ACC be detectable and interpretable by human drivers. They count four basic factors for safe operation of ACC.

1) The dynamic behavior of the ACC system should be predictable by the driver;
2) The ACC should decrease physical workload without placing unrealistic demands on attentional management and human decision-making;
3) The transfer of authority between automation and human should be seamless;

4) The operational limits of ACC performance should be easily identified.

Research shows that drivers are less likely to use ACC in heavy traffic and are more likely to engage it when driving in the fog, driving at night on an unlit highway, driving for longer periods of time, driving in low density traffic, and driving on an unknown road network [81]. In [82] and [83] some results on field experiments with ACC equipped vehicles are explained.

The number of studies on human factor issues of CA/CW systems are not as much as those for ACC. However, it is interesting to note that preliminary human factor guidelines for crash avoidance and warning systems are developed for NHTSA a few years ago [84]. A similar guideline [85] is prepared for AHS designers. These guidelines are based mainly on existing human factor handbooks and engineering texts and discuss functional requirements, interface philosophy, selection and design of control and displays and design of driver-system dialogues.

In assessing driver-warning systems, Dunges [86] believes that the difficulty in getting exact knowledge of driver's intention by technical sensors will cause the warning systems to generate frequent false alarms. He adds that action recommendation systems or even automatic control systems can be safer than warning systems as long as such misunderstandings of driver's intended action exists. This point of view is different from the belief that warning systems are more conservative measures among the possible driver's assist systems.

Based on three publicly available empirical studies Stanton and Young [87] conclude that automation can reduce driver's mental workload to a certain degree. Also they suggest that automation leads to greater predictability and smoothness of the vehicle handling, which reduces driver stress. However, they observed that sometimes drivers had difficulty in reclaiming vehicle's control. Then they discuss a few psychological key issues that are pertinent to vehicle automation and those are the following:

1) locus of control which is the extent to which removal of control from the driver affects performance of the vehicle;
2) trust of the driver in the automated system;
3) situational awareness of the driver about the operational status of the technological system and the driving context;
4) the mental representation that the driver builds up of the automated system;
5) mental and physical workload associated with automation;
6) feedback of the state of the system to the driver in an effective manner;
7) driver stress.

There are few research papers that address the driver interface. Serafin [88] uses computer simulated ACC experiments to determine driver preferences for the adjustable distance control labels for ACC. A driving simulator study has been carried out by Stapleford *et al.* [89] to develop possible guidelines for designing and positioning the visual interface of an ACC system. A brief description of ACC driver interface can also be found in [13], [14]. Lloyd *et al.* [90] provide a good comparison of different possible warning methods to the driver and propose a brake pedal pulsing methodology as a better alternative for CWS. Seiler *et al.* [39] propose a graphical gradual light display to warn the driver of the risk of a rear end collision. Driver interfaces of some existing collision avoidance systems is assessed in [91] and guidelines are proposed for design of driver interface of CW/CA systems.

Human factor issues are not exclusive to driver assist systems. Many sectors of technology conduct HF research for their products and the field is well-established with a vast body of knowledge which can serve as a good source for designers of driver assist systems. Test results for identifying human driver's driving habits are available and could be used to establish a baseline for performance of the driver-assist system. However, we think more human-in-the-loop tests are needed with vehicles that are equipped with such assist systems. The results of these tests should pinpoint the problems specific to each system. Such tests should focus on driver mental workload and objectively assess driver situation awareness with the assist system. The results should help design systems that keep a good balance between decreased driver workload and his/her situational awareness. For ACC, the major design concern should be following distances that are compatible with driver age, gender and preferences and the traffic condition. The operational limits should be clearly conveyed to the driver. For CA/CW detection of driver's situation alertness is a challenging task which needs more research. Timely and accurate determination of driver alertness can increase the safety and improve reliability of the system by reducing false alarms. Driver interface design for CA/CW systems is open for more research. Haptic interfaces have been researched in other fields and the available knowledge can be extended for assist systems as well. More research on the government side can improve the available HF guidelines and could possibly extend to standards for the manufacturers. Addressing HF issues is key for industry in developing marketable driver assist systems. Panel discussions and workshops similar to ones held are especially important for a better understanding of HF issues.

V. Legal and Institutional Issues

Previous sections of this paper discussed the safety implications of driver assist systems to some extent. The discussed driver assist or warning systems can potentially improve the safety of the roads, but may change the character of automobile accidents. Therefore, there is the possibility that introduction of these systems shift the liability distribution from the motorists toward the manufacturer of the product. The potential legal liability and cost of liability insurance for the manufacturers might discourage the rapid development and widespread deployment of assist systems. Understanding legal influences of driver assist systems certainly requires more research. Consequent national governmental will and support in terms of legislative measures can ease many of the current complications of such a "venture." The available published research reports that analyze the legal and institutional difficulties of driver assist systems are very few. The few existing reports and papers mainly discuss the legal issues of automated highways (AHS) rather than mere vehicle level automation. However, due to many common issues, these studies provide a good understanding of legal and institutional influences of vehicle level automation as well.

A very informative account of liability and insurance implications of such driver assist systems is provided by Syverud [92]. He first briefly discusses the current United States legislation for automobile accidents and the subsequent lawsuits. With current pattern of accidents, the negligence trials against owners or drivers of vehicles outnumber those against manufacturers or highway owners. Most of the liability costs of the accidents are paid by car owners, through their own liability insurance. Syverud explains how different driver assist warning or information systems might shift the liability distribution toward the manufacturer or highway owners (for intelligent highway systems). For driver information/warning systems, he proposes techniques that manufacturers can use to reduce the liability costs without massive tort law reforms:

1) providing product warnings;
2) recording and documenting the performance of assist systems;
3) buying liability insurance covering the warning system;
4) having an independent producer/installer with fewer assets produce/install the system after the car is purchased by the consumer;
5) persuading the state legislatures to enact laws that failure of a warning system can not be used as a defense in a negligence suit;
6) cooperating with federal agencies in implementing driver warning systems in accordance with guidelines promulgated by federal government.

The case is a little more complicated for vehicle control systems that automate some driving tasks. While such systems can generally improve the safety, system failure in such cases can have catastrophic consequences. System manufacturers and highway owners are more likely to be the defendants in a tort suit. For controlled highways specially, a failure can involve many vehicles resulting in numerous lawsuits against manufacturers and highway owners. Syverud [92] reviews some federal legislation promoting other breakthrough new technologies and based on his review, he suggests federal indemnification for catastrophic liability. While his discussion mainly addresses automated highway systems, it is informative on the vehicle level automation as well.

Costantino [93] looks into some other institutional barriers to development of IVI mainly from the government point of view. He explains the studies of Institutional and Legal Issues Committees established by IVHS America to understand potential nontechnical constraints to IVHS implementation. In a more recent paper, Khasnabis *et al.* [94] discuss the government liability for automated highways and elaborate on sovereign immunity issues and the required standards. They analyze the practical measures that can be taken by the government which exempts the government agencies from lawsuits in IVHS related accidents without undermining the interests of the citizens or discouraging private investment for development. The above-mentioned references evaluate the problem under United States laws. Feldges [95] presents a similar analysis for the German legal system.

There are common or particular interests between the government agencies, private companies, academic and research institutes in advanced vehicle and highway control systems. The government agencies are more interested in increased road safety and improved traffic condition and the private sector's interest is in more marketable products. Therefore each sector has more or less invested in research and development of such systems. Currently the Transportation Research Board has a legal program compromising of seven technical committees. One of these committees deals with emerging technologies and draws on attorneys from state and local government. Also annual meetings and workshops are held by TRB which address a broad range of subjects on transportation laws. These meeting and workshops can serve as a good medium to communicate the legal and institutional issues of driver assist systems. Academic units have contributed substantially to both public and private research relying on their multidisciplinary scientific resources. The common trend in recent years has been more toward formation of alliances between the public, private, and academic institutions and a kind of international and multidisciplinary cooperation has preceded national and international competitions especially in advanced highway system research. Chen and French [96] have provided a more detailed account of organizational response to intelligent transportation systems and the difficulties that exist. They have reviewed the structure of the organizational activities across Europe, United States and Japan toward materialization of advanced highways, which can also be helpful for future decision-making in the related areas such as IVI.

VI. Concluding Remarks

The recent trend of research on development of driving assist systems was reviewed in this paper. The focus was on ACC, collision warning and collision avoidance systems and their impact on driver's comfort, safety and traffic flow. The advances in AHS were also briefly investigated as they have a lot in common with the aforementioned vehicle-level driver assist systems. AHS serves a more futuristic purpose and due to the many financial, technical, and institutional barriers that are in its way, is unlikely to materialize in near future. The vehicle based assist systems on the other hand have fewer barriers to pass before they can find widespread use. As a result these systems have attracted special attention and some have reached the production line. It is quite ironic however, that the benefits and deficits of such systems are not completely understood yet.

The ways in which ACC systems can improve driver comfort are explained, and at the same time different viewpoints of the safety of ACC are discussed. Some researchers support the idea that reduced driver workload can help the driver for a safer control of the vehicles while others believe that a poor design for ACC with very low attention demand can be potentially hazardous. There is also a lot said about the impact of ACC on traffic flow. While there is almost unanimous agreement that with ACC equipped vehicles, a smoother traffic flow is possible, the effect on the capacity of the highways has been looked at from two different perspectives. A safe and comfortable design requires longer headway between the vehicles. Abiding to this design will decrease road capacity. However, shorter headway times that do not reduce highway capacity are not totally ruled out. Stable following with very short headway times which can considerably and safely improve the capacity of highways is possible with some means of communication between the vehicles, which looks like a longer term goal for automation.

Collision warning and avoidance systems have the added complexity that they should be able to recognize a hazardous situation and communicate it to the driver. This is in contrast to ACC system for which the driver has the responsibility to supervise. However, there are similarities in sensory requirements and control methodology. The human factor issues are of great importance for CW/CA systems and therefore a section in this paper was dedicated to this subject.

The less researched area of legal and institutional barriers for vehicle automation was also discussed. These issues could potentially hinder the market implementation of many of the full-automation systems. These may even include systems that one technologically rendered feasible.

The future research for ACC needs to focus more on determining appropriate following distance for different drivers. The global impact of ACC on traffic flow is another issue to look more into. Collision avoidance and many CWS are in a less mature position and need more research in various areas. Human factor issues are especially important for CW/CA systems. Detection of driver alertness is a challenging task and will ensure timely and effective warning/evasive action. Most available control actions are tailored for mild automated maneuvers. For collision avoidance or stop and go ACC more aggressive control actions might be needed. So in the control design operational limits of the vehicle and actuator saturations are additional issues to be considered. For collision avoidance the brake or steering might operate close to their limits and therefore more accurate modeling of these components might be necessary. Legal issues are serious considerations before CA/CW can be widely deployed. Special research on the government side is necessary to remedy solutions which will encourage manufactures in developing such systems. Moreover guidelines and possibly standards can be devised by the government to regulate design of driver assist systems.

This review of the research on driver assist systems for ACC, collision warning and avoidance systems, provides a convenient way of evaluation of the recent research advances in the field. It serves as a thorough reference for researchers and engineers in automotive and highway engineering and will also be an introduction for those who are less familiar with the subject.

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Dr. Eskandarian is a Member of the Society of Automotive Engineers (SAE), American Society of Mechanical Engineers (ASME), New York, Sigma Xi professional societies, and Tau Beta Pi and PI Tau Sigma engineering honor societies. He recently received the *Recognition Award for Service* from the FHWA/NHTSA National Crash Analysis Center.