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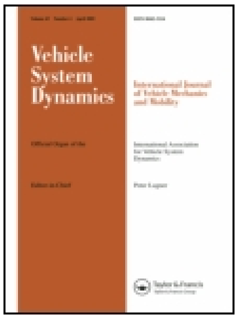

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A comprehensive review of the development of adaptive cruise control systems

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It has been 15 years since the first generation of adaptive cruise control (ACC)-equipped vehicles was available on the market and 7 years since the ISO standard for the first generation of ACC systems was produced. Since the next generation of ACC systems and more advanced driver-assistant systems are at the verge of complete introduction and deployment, it is necessary to summarise the development and research achievements of the first generation of ACC systems in order to provide more useful experiential guidance for the new deployment. From multidimensional perspectives, this paper looks into the related development and research achievements to objectively and comprehensively introduce an ACC system to researchers, automakers, governments and consumers. It attempts to simply explain what an ACC system is and how it operates from a systematic perspective. Then, it clearly draws a broad historical picture of ACC development by splitting the entire history into three different phases. Finally, the most significant research findings-related ACC systems have been reviewed and summarised from the human, traffic and social perspectives respectively.

Keywords: adaptive cruise control; stop&go ACC; full-speed ACC; cooperative adaptive cruise control; advanced driver assistant systems; automated highway system

1. Introduction

According to the latest surveys, there were nearly 6,420,000 vehicle accidents in the United States in 2005. The financial cost of these crashes was more than 230 billion dollars. Approximately 2.9 million people were injured and 42,636 people were killed [1]. It is estimated that 90% of accidents occur due to human error, potentially induced by distraction, poor judgement or lack of situation awareness [2]. There is no denying the fact that the increasing number of traffic accidents and traffic congestion are extremely serious social problems that governmental, academic and industrial entities should take strong measures to deal with cooperatively.

In recent decades, advanced driver-assistant systems (ADAS) have been developed and are being developed to enhance driving comfort, reduce driving errors, improve safety, increase traffic capacity and reduce fuel consumption [3]. The most popular research on ADAS has

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recently been focused on adaptive cruise control (ACC) systems, which are now commercially available in a wide range of passenger vehicles and are the focus of researchers, automakers, governments and consumers across the world. The first generation of ACC systems was included in some luxury vehicles by automakers and their suppliers primarily from the viewpoint of enhancing driving comfort and convenience with some additional potential increase in safety [4,5]. Until now, most automakers across the world have made ACC systems available in their luxury vehicles with a tendency to extend this feature from the high-end vehicles to the mid-range vehicles [6,7].

Apart from the design process of an ACC system, several related key issues have been concerned by the researchers, automakers, governments and consumers across the world from theoretical research, system development, component implementation, product manufacturing to market deployment (Table 1). These issues can primarily be categorised into three types: human issues, traffic issues and social issues. Human issues involve the relationship between ACC systems and humans, and include driver-behaviour issues, user-acceptance issues and human–machine issues. Traffic issues involve the relationship between ACC systems and traffic, and include safety issues, capacity issues and stability issues. Social issues involve the relationship between ACC systems and society, and include environmental issues, marketing issues and legal issues. These three types of issues still need to be clearly addressed with a higher ACC penetration. In particular, increased traffic capacity, improved traffic flow stability and reduced fuel consumption are still controversial issues [5]. Furthermore, with the increasing ACC penetration, research on these three types of issues will gradually require more real traffic data collection and real traffic operational tests to complement and verify the recent results with simulations and small-range field operational tests.

The first generation of ACC systems have been on the market in Japan since 1995, in Europe since 1998 and in North America since 2000 [7]. However, no comprehensive review papers or publications have been published on the subject, with the exception of a few [4,5] that present only limited research achievements. ACC systems are the first logical step in a progressive path leading to an ADAS. Hence, it is necessary to conduct a comprehensive review before the next generation of ACC systems are introduced to the market or before the future ADAS are deployed. This paper provides an overview of developments and research achievements to objectively and completely introduce ACC systems to researchers, automakers, governments and consumers from a multidimensional perspective. The remainder of this paper is structured as follows. The definition, concept, components, structure and design of the system are briefly presented in Section 2 to comprehensively demonstrate what an ACC system is and how it operates. Section 3 draws a clear historical picture of ACC system developments worldwide by splitting the entire history into three different phases: the early preparation phase, the intermediate implementation phase and the latest product phase. Section 4 presents the relationship

Table 1. Related focuses towards different stakeholder.

Focuses	Researcher	Automaker	Consumer	Government
Driver-behaviour	•	•	•	
User-acceptance		•	•	
Human–machine		•	•	
Safety	•	•	•	•
Capacity	•			•
Stability	•			
Environment	•	•		•
Market				
Law				•

between ACC systems and humans by analysing human-behaviour issues, user-acceptance issues and human–machine issues. Section 5 presents the relationship between ACC systems and the traffic system by analysing safety issues, capacity issues and stability issues. Section 6 presents the relationship between ACC systems and society by analysing environmental issues, marketing issues and legal issues. Section 7 presents the conclusions which proposing the potential challenges and tendencies of ACC systems.

2. Systematic perspective review

2.1. *System definition*

ACC systems are an extension of conventional cruise control (CCC) systems that adjust vehicle velocity and provide a specified distance to the preceding vehicle by automatically controlling the throttle and/or the brake. One key part of an ACC system is the range sensor (such as radar, lidar or a video camera), which measures the distance and the relative velocity of the two successive vehicles. In the absence of a preceding vehicle, an ACC-equipped vehicle travels at a user-set velocity by controlling the throttle, much like the operation with a CCC system. When the preceding vehicle is detected, the ACC system calculates and then estimates whether or not the vehicle can still travel safely at the user-set velocity. If the preceding vehicle is too close or is travelling slowly, the ACC system shifts from the user-set velocity control to the user-set time headway control by controlling both the throttle and the brake. The deployed ACC system operates in a limited velocity range from 40 to 160 km/h and under a maximum braking deceleration of around 0.5 g [8]. In the real driving scenarios, the driver has ultimate control of the ACC-equipped vehicle when required.

2.2. *System concept*

The first term for the ACC was adaptive intelligent cruise control (AICC); this term was adopted from the PROMETHEUS programme in Europe, but is considered to be somewhat inappropriate due to the potential for the word ‘intelligent’ to raise expectations of performance to unrealistic levels [9]. Hence, the term ‘ACC’ has been adopted to refer to the autonomous longitudinal following control that provides the driver with comfortable and potentially safe driving. Before the term ‘ACC’ was applied by the ISO 15622 [10], several additional terms (listed in Table 2) were adopted by different researchers and automakers in different literature. With the development of communication technologies and the international standard of dedicated short range communications (DSRC) (ISO 15628: 2007 Road transport and traffic telematics - DSRC - DSRC application layer) [11], researchers have gradually paid more attention to non-autonomous longitudinal following control in order to truly improve traffic safety, traffic capacity, traffic flow stability and driver comfort by adding Vehicle–Vehicle/Road–Vehicle communication [12–17].

2.3. *System components*

ACC systems are built as distributed systems using common electronic control units (ECUs) plus one additional ECU. The common ECUs are slightly modified by the current standard ECUs, such as the engine control module, brake control module and transmission control module; the additional ECU is called the ACC control module since it is composed of a range sensor and the ACC controller [6]. The long range radar (LRR) sensor and the light detection

Table 2. The different terms which are related to 'ACC'.

Type	Autonomous	Non-autonomous
Concept	Only on-board information [18]	Both on-board and other reference information [18]
Term	Intelligent Cruise Control [19] Autonomous Intelligent Cruise Control [20] Automatic Cruise Control [22] Active Cruise Control [24] Advanced Cruise Control [26] Auto-Adaptive Cruise Control [27]	Semi-Autonomous Adaptive Cruise Control [21] Coordinated Adaptive Cruise Control [23] Cooperative Adaptive Cruise Control [25]

and ranging (Lidar) sensor are commonly used in the first generation [28]. To improve the safety and usage rate of an ACC system, mid- and short-range radar, video cameras and thermal radiation sensors will be applied in the next generation [28,29]. The literature has broadly introduced the functionalities and the advantages/disadvantages of the various range sensors and has made comparisons between them [28–32]. To improve the rate of user-acceptance of ACC systems, automakers and researchers have paid increasing attention to the human machine interface (HMI), which consists of operating switches, displays, warning devices and pedals (accelerator and brake). The HMI is designed in such a way that the driver always feels that the system is providing support in the best way and that the driver has full control of the vehicle [28,33]. To assist in the operation of an ACC system, several related sensors (such as curve and velocity sensors) are broadly applied. Curve sensors usually include the steering angle sensor, yaw rate sensor, lateral acceleration sensor, navigation system (digital map and course calculation) and video camera; these assist the driver in predicting the future course of the highway, especially when driving along curves or during lane changes [6]. To improve the effective operation of ACC systems, all of the parts mentioned above are usually connected via a CAN BUS or/and LIN BUS [6,24,34,35].

2.4. *System structure*

According to the signal flow and operating process of an ACC system, the system's architecture can be split into four major parts, which are illustrated in Figure 1: signal collecting (SC), signal processing (SP), signal actuating (SA) and signal displaying (SD) parts [6,8,34,36,37].

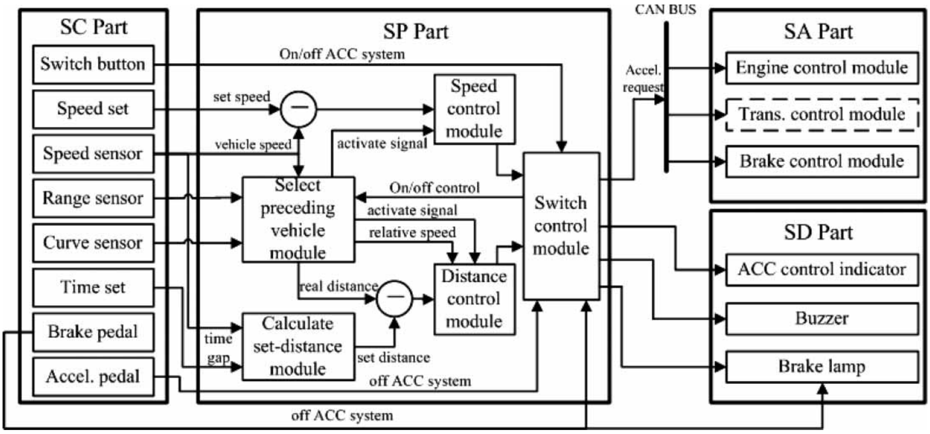

Figure 1. ACC system architecture.

The operating process is as follows. The switch control module always detects the ON/OFF signal during driving. If the switch button is pressed to the ON position and the velocity and time headway have been set by the driver, the switch control module activates the ACC system. The range sensor starts to detect the preceding objects. If the preceding objects are not available or are far away and running fast, the speed control module is activated by selecting the preceding vehicle module; then, the vehicle automatically operates in the velocity control state with the user-set velocity of the speed control module, which controls the engine control module (transmission control module is an option). If the preceding objects are available and too close or running slowly, the distance control module is activated by selecting the preceding vehicle module; then, the vehicle automatically operates in the spacing control state with the user-set time headway of the distance control module, which controls the engine control and brake control modules (transmission control module is an option). If the switch button is pressed to the OFF position or either the brake pedal or the acceleration pedal is pressed by driver, the switch control module turns off the ACC system. During the ACC system's operating process, the ACC control indicator displays the operating state (velocity control state or spacing control state). If the deceleration capability of the ACC system is insufficient due to the imposed limitations, the buzzer is activated to request that the driver to take over control of the vehicle. If the brake pedal is pressed by the driver or if the brake control module is activated by the switch control module, the brake lamp turns on.

2.5. *System design*

Any design of an ACC system begins with the selection and design of a spacing policy [38]. The spacing policy refers to the desired steady state distance between two successive vehicles. Discussion of spacing policies goes back to the 1950s; Pipes [39] proposed a spacing policy that was called the idealised 'law of separation'. It is the sum of the distance that is proportional to the velocity of the following vehicle and a certain given minimum distance of separation when the vehicles are at rest. Then, spacing policy research is deeply focused on the longitudinal control of the personal rapid transit (PRT) system [40,41], but the concepts and conclusions can be directly applied to ACC systems [42]. Three basic spacing policies (constant distance, constant time headway (CTH) and constant safety factor spacing) have been proposed for the PRT system [40–42]. Some nonlinear spacing policies have been proposed to improve traffic flow stability [3,43,44], these policies are called constant stability spacing policies. Han and Yi [45] proposed a drive-adaptive range policy to improve the rate of user-acceptance; this policy is called the constant acceptance spacing policy. Hence, five different kinds of spacing policies have been proposed by earlier research: constant distance, CTH, constant safety factor, constant stability and constant acceptance. By considering feasibility, stability, safety, capability and reliability [40–46], the CTH spacing policy is applied to ACC systems by automakers.

The controller architecture for the ACC-equipped vehicle is typically designed to be hierarchical, with upper and lower levels [8]. The upper level controller is called the ACC controller, while the lower level is called the longitudinal controller. The ACC controller determines the desired acceleration that is transmitted to the longitudinal controller. The longitudinal controller determines the throttle and/or brake command, which is required to track the desired acceleration [8,47] and returns the fault messages to the ACC controller [8]. The ACC controller should be designed to meet three performance specifications: individual stability [8], string stability [8,48,49] and traffic flow stability [12,43,50,51]. Vehicle dynamic models, engine maps and nonlinear control synthesis techniques [52–56] are used by the longitudinal controller to calculate the real-time brake and throttle inputs that are required to track the desired acceleration. The longitudinal controller has shown that even the PID or its modifications could work very well [19,20,56]. Some other more complex algorithms have also been proposed and analysed [57,58]. Some criteria have been taken into account by automakers to implement the ACC controller and the longitudinal controller [6,24], such as no impact on vehicle safety, no reduction in the availability of basic vehicle functions, low hardware effort, low application effort and small variation in components. All of these criteria can be fulfilled by slightly modifying the existing ECUs and by adding one new ECU that combines the range sensor and the ACC controller.

Naturally, the test procedure will be performed to verify the selected spacing policies and designed controllers. The test procedure can be split into three parts: a computer simulation test, a lab platform test and a field operational test. The computer simulation and lab platform tests, which are considered to be the effective and feasible methods for academic researchers, require that a control model, vehicle/sensor model, traffic flow model and driver model be built. How to evaluate the designed ACC system will be considered broadly in later sections. Some computer simulation tools have been developed for the study of ACC systems and highway traffic to facilitate the tests and determine design expectations [47,59]. The models that are used in these simulation tools can be categorised into two different types: macroscopic models and microscopic models [47]. Thus far, microscopic software simulators have been developed and applied to the simulation test, such as MITSIM [60], DS [47], PELOPS [61], UMACC [47], ACCSIM [62] and SmartAHS [63]. Up to now, the first generation of ACC systems has been available to the worldwide market. Private automakers and their suppliers must conduct various FOTs independently to make sure that the system works effectively. However, most of the results and methodologies are not documented or reported in the open literature, but are being kept secret in order to enhance competitive advantage. BOSCH tested its own ACC system on over 40,000 test kilometers. The technical functionality and safety of the system were demonstrated in real-world traffic situations [6]. Large-scale field tests have also been performed in the USA [64–66] by Fancher's group at the University of Michigan's Transportation Research Institute (UMTRI); the tests randomly selected 108 drivers who drove ACC-equipped vehicles on normal roadways. In Europe, a FOT was conducted in three countries with ACC-equipped vehicles to assess the driver-following behaviours [4].

3. Historical perspective analysis

Currently, increasing traffic congestion and traffic accidents are serious social problems that compel governmental, industrial and academic entities to alter transportation systems radically in order to make them more efficient, more comfortable and safer [67]. ACC systems are the first logical step in a progressive path that leads to a future automated highway system (AHS), and are also the first available product to improve passenger comfort with potential driving safety improvement. This section draws a clear historical picture of worldwide developments in ACC systems by splitting the entire history into three different phases: the early preparation, medium implementation and latest product phases.

3.1. *Early preparation phase (1950–1985)*

ACC systems are usually viewed as an extension of CCC systems since they additionally enable vehicles to follow a slower preceding vehicle automatically [6]. The history of CCC systems can be traced to the 1950s [68]. The earliest CCC system could only hold the throttle in a fixed position using mechanical parts and did not offer much functionality. In the late 1950–1960s, CCC system controllers with proportional feedback were available to provide full throttle when vehicle velocity dropped 6–10 mph below the desired cruising velocity; however, these earlier systems did not maintain the vehicle's velocity or increase safety or driving comfort until the 1970s. In the 1980s, with increases in availability, functionality, flexibility and reliability and a decrease in the cost of microchips, and with the other pushes for component integration, part reduction and ease of assembly, CCC systems were generally made easier to operate, more reliable and more robust, and they performed their basic functions in a much more efficient manner than the earlier systems. Currently, a large number of CCC-equipped vehicles are still running on the road [69].

The history of ACC system development began well before the term 'ACC' was adopted, and traced to the 1960s [47,62]. Diamond and Lawrence [70] proposed the development of an automatically controlled highway system (ACHS) to deal with increasing traffic congestion in April 1966. This initiative was an attempt to give the student a unique experience in design education; there was a great innovative effort to develop an ACHS, which is nearly identical to an ACC system. After background studies in traffic safety, traffic congestion, electronic highways and consumer acceptability, as well as completion of an analysis of vehicle dynamics, a system controller was designed to carry out the velocity, spacing, steering and mechanical actuator controls. In addition, Diamond and Lawrence also investigated the economic feasibility of an ACHS. This research was supported by the industry programme of the college of engineering at the University of Michigan in 1966. Levine and Athans [71] proposed to use the theory of optimal control to design an optimal linear feedback system to regulate the position and velocity of every vehicle at a steady state in a densely packed string of high-speed moving vehicles while applying the simplest three-vehicle string model to verify their design by analogue computer simulation in July 1966. Their research was supported by the US Department of Commerce under Contract C-85-65 (Project Transport) during the 1960s.

The closest research to ACC systems was the development of automatic vehicle following control systems. Shladover [9] categorised these systems into 13 controller structures based on the diversity in sources of feedback information. In particular, the controller structure of ACC systems matches 'Structure 2', in which the feedback information includes the spacing and velocity difference relative to the immediately preceding vehicle. Automatic vehicle-following studies were conducted in 1964–1971 at the Ohio State University (OSU) [72]. The first published technical paper to describe this kind of controller structure appeared in 1968 for the analysis of highway automation by Fenton's group at OSU [73]. They proposed that the controller structure must meet several requirements [72–75], which have been applied to define an ACC controller's design: maintaining individual vehicle stability and string stability, choosing a fixed speed when without a preceding vehicle, improving driving comfort and minimising the time headway to improve traffic capacity. They divided the spacing-velocity difference phase plane into six regions and defined different control laws for these regions [72]. This controller design was simulated extensively for the two-vehicle case, and has also been tested in a full-scale vehicle on a test track using a 'phantom' lead car or a mechanical take-up reel (or yo-yo) mounted between two vehicles to provide spacing and velocity difference measurements. From 1964 to 1980, this research was initially sponsored by both the Ohio Department of Highways and the US Bureau of Public Roads, then by the US Department of Transportation and finally by the Federal Highway Administration/US Department of Transportation [72]. Other researchers also investigated this controller structure in considerable depth via analysis and simulations using the second-order vehicle dynamic model [76,77] or the third-order vehicle dynamic model [78,79]. Significant longitudinal control system projects were organised during the 1970s in Europe, such as the Cabinentaxi system in Germany [80] and the ARAMIS system in France [81].

However, the efforts of the earliest research failed due to the severity of the congestion problem and the fact that the state of the art control, communication, computer and sensor technology did not meet the requirements of the development programs [82]. Unfortunately, Diamond and Lawrence's group did not continue their work because of technical, sensor and funding problems [70]. Fenton's group switched from the vehicle following to the point following approach in 1971 due to the unavailability of radar sensors that could meet their performance needs [72]. However, research into CCC systems provided the concept of 'cruise control', while research into automatic vehicle following control provided the concepts of 'adaptive', 'intelligent' and 'autonomous' systems. Fortunately, the early research activities built a strong theoretical and technical foundation for the implementation phase to follow.

3.2. *Intermediate implementation phase* (1986–2000)

By the 1980s, the infrastructure of the transportation system had not kept pace with the rapid expansion in the number of vehicles around the world. Thus, more congestion, accidents, air pollution, driving stress and the other discomforts forced governmental, industrial and academic entities to undertake strong measures in pursuit of the implementation of ACC systems [67,83]. With the availability of improved communication, computer and sensor technologies, the intermediate implementation phase began in 1986 with almost parallel actions in Europe, the US and Japan [84].

3.2.1. *Europe*

In Europe, the eight-year PROMETHEUS programme was initiated on 1 October 1986 by 16 automotive companies cooperating with 56 electronics and supplier companies and 115 basic research institutes [83], with funding support from the European Community's EUREKA programme and the governments of the major western European countries [9,85]. Under this programme, the European automotive industry expanded its topics of research from a vehicle-only focus to the transportation system with the vehicle as the key element. This revolutionary new approach was characterised by recognising the full recognition of vehicles as sensors and actuators of a future road traffic control system rather than passive objects of traffic research [83]. One of its main intents was to provide a framework for cooperative development at the pre-competitive stage of technologies that could be used by the European automotive industry and supplier industries to improve the worldwide competitive standing of the European automotive industry relative to their counterparts on other continents [9,83].

In September 1991, an interim demonstration of the achievements of the PROMETHEUS programme was given to policy makers for European research, transport and industry in Torino; this event was called the Board Member Meeting' 91 [83]. The 10 Common European Demonstrators (CEDs), which are considered the application system prototypes, were shown at the Fiat test track [86,87]. The term AICC was adopted as one of the CEDs. A nine AICC-equipped vehicle demonstration was conducted to evaluate range and angular accuracy, as well as the robustness of the range sensors to environmental conditions [83,86].

Broqua et al. [88] defined the term 'ACC' and described an ACC system in detail. They applied the enhanced SPEACS micro-simulator to assess their defined and designed ACC strategies under stationary and real-traffic situations. Zhang [89] defined several levels of longitudinal control that were considered within PROMETHEUS: distance-warning systems, ACC and 'light convoy'. Zhang and Benz [90] defined a modelling framework for evaluating the performance and safety of ACC systems without showing any specific system's design features. Actually, a large proportion of the work was conducted as proprietary development work by private automakers and their suppliers rather than publicly funded academic research. The automakers included BMW, Daimler-Benz, Fiat, Jaguar, MAN, Opel, Porsche, PSA, Renault, Saab, Volvo and VW [91]. The suppliers included Bosch, Celsius Tech., DASA, GEC-Marconi, Husat, Leica, Lucas and Pilkington [91]. Hence, most of the results and methods are not documented in the open literature, but kept secret in order to enhance competitive advantage. Opel and Daimler-Benz in Germany both developed true AICC units through PROMETHEUS that were first tested in mid-1994 [92]. BOSCH [6] and BMW [24] each introduced the main components and system architectures of their ACC systems without showing detailed test data of FOT.

At the end of the PROMETHEUS programme in 1994, the opportunity for continued research with ACC systems was greatly reduced [92]. Most subsequent projects focused on the evaluation and evolution of different ACC systems [85]; the UDC project [93] was aimed at evaluating the impact of ACC systems on the urban environment, while the AC-ASSIST project [94] cooperated with Jaguar, Rover, Renault and Volvo [92] to evolve ACC systems through prototype refinement, simulator tests and test track trials.

3.2.2. *USA*

The PROMETHEUS programme gave Europe an initial edge over the U.S.A. in the advancement of advanced vehicle control systems (AVCS) [91]; work on ACC systems in the USA lagged somewhat behind that in Europe [9]. By the mid-1980s, urban traffic congestion became a major concern of the FHWA, state transportation departments and related agencies, who organised serious discussions and generated proposals for major research programmes to deal with traffic congestion problems [67].

In 1986, the California Department of Transportation's (Caltrans) collaboration with the Institute of Transportation Studies at the University of California Berkeley initiated a small effort to study the use of automation in vehicle-highway systems. This effort led to the development of a California state-wide programme called PATH [9,67]. Caltrans-PATH was involved in a robust AHS research project and an additional 35 'base' funding projects in areas such as collision warning, vehicle control and automation concepts [7]. The task of MOU 392, which was supported by Caltrans, PATH and the Ford Motor Company, was to design and simulate ACC controllers [95] and to develop throttle and brake control systems [96] at Ioannou's group at the Advanced Transportation Technology Centre at the University of Southern California. Ioannou's group also conducted the MOU 248 task [97] to evaluate cooperative driving systems, including ACC systems, through experimentation, and Task order 4217 [98] to evaluate the effects of ACC systems in the mixed traffic. The task of MOU 390, which was supported by Caltrans - PATH, was conducted by Darbha's group [99,100] at Texas A&M University to research ACC systems and their effect on string stability and traffic flow stability.

In 1988, Caltrans and PATH gradually realised that without federal support and the widespread support of private industry and transportation experts across the country, a sound AHS effort would not be possible [101]. Caltrans and PATH stimulated their counterparts in other states to join forces in the creation of Mobility 2000 to define a programme of national scope [102]. Mobility 2000 grouped intelligent vehicle highway system (IVHS) technologies into four functional areas: ATMS, ADIS, CVO and AVCS [101,102]. The first generation of ACC systems, which falls within the scope of AVCS, was considered to be a type of driver assistance implemented mainly by automotive industry [7]. In 1997, the focus of the work was changed to emphasise near-term safety research under the nine-year Intelligent Vehicle Initiative (IVI) programme [7]. IVI's mission was to prevent highway crashes and the fatalities and injuries that crashes cause. IVI's objectives were developed in support of this overall mission

[103]. Rear-end collision is the most important research area because it is the most predominant crash type. A five-year automotive collision avoidance system (ACAS) field operational test project was initiated in June 1999 to assess the performance of rear-end collision warning systems and ACC systems in operational environments via joint research between the US DOT and the General Motors Corporation [104]. In this project, the performance, effectiveness, potential safety benefits and user-acceptance of ACAS and ACC systems were evaluated.

A large-scale ACC system field operations test was conducted by Fancher's group [64–66] from July 1996 to September 1997 in cooperation with the National Highway Traffic Safety Administration (NHTSA) and UMTRI. The field operations test was performed in Michigan and involved 108 volunteers driving ten ACC-equipped Chrysler Concordes. Additionally, an ACC system evaluation project [65] sponsored by the NHTSA was conducted by Fancher's group from August 1997 to October 1999. The Volpe National Transportation Systems Center, with the support of the Science Applications International Corporation (SAIC), conducted another independent evaluation project of ACC systems for NHTSA. The overall goals of the large-scale evaluation project were as follows: determination of the safety effects of ACC systems, ACC-equipped vehicle performance, user-acceptance of ACC systems and system deployment issues.

3.2.3. *Japan*

In the late 1980s and the early 1990s, the Japanese government (the National Police Agency, the Ministry of International Trade and Industry, the Ministry of Transport (MOT), the Ministry of Posts and Telecommunications (MPT) and the Ministry of Construction (MOC)) initiated their IVHS projects, respectively the Vehicle Information and Communication System, Universal Traffic Management System, Advanced Safety Vehicle (ASV), MOC-Intelligent Transportation System and Super Smart Vehicle System [105]. This could be quite confusing to outsiders because the competing-ministries sponsored projects that appeared to cover much of the same ground [9]. Hence, the Vehicle, Road and Traffic Intelligence Society (VERTIS) was organised in 1994 as a counterpart to the Intelligent Transportation Society of America (ITS America) and the European Road Transport Telematics Implementation Coordination Organization [105,106]; it was renamed ITS Japan in June 2001 [107]. The Advanced Cruise-Assist Highway System Research Association (AHSRA) was established in September 1996 as an AHS research and promotion organisation [106]. Currently, the major Japanese ITS programmes (such as the AHSRA and ASV programme) are centred within the Ministry of Land, Infrastructure and Transport, which was integrated by MOC, MOT and MPT in 2001 [7,107].

Unfortunately, it is extraordinarily difficult to develop a clear picture of the development of ACC systems and collision avoidance/warning systems in Japan because most of the work was conducted by private automotive companies and their suppliers; also, most government documents and some of the research results were published in Japanese [9,67,105]. However, some valuable information can still be obtained from limited sources. Mazda, Mitsubishi and Toyota developed fully automated vehicles that were tested on test tracks [67]. The latest ASV programme mainly focused on the development of autonomous active safety systems, and all Japanese automakers were involved. A crash avoidance system was the focus of the ASV-1 programme from 1991 to 1995; then, the focus of the ASV-2 programme was transferred to a full-speed ACC system from 1996 to 2000 [7].

3.3. *Latest product phase (*2001*-present)*

Currently, 'ACC' is not only a technical term, but also a popular marketing term. Consumers are gradually becoming familiar with it from different sources and consider paying for it even

Table 3. The ACC-equipped vehicles available on the market.

Region	ACC-Vehicles
Europe	Audi A6, Audi A8, Audi Q7, BMW 3 Series, BMW 5 Series, BMW 7 Series, Jaguar XK-R, Jaguar S-Type, Jaguar XJ, Mercedes-Benz S-Class, E55 AMG, CLS, SL, CL, ML, Range Rover Sport, Volkswagen Passat, Volkswagen Touareg, Volkswagen Phaeton, Renault Vel Satis, Volvo S80, Volvo V70, Volvo XC70.
USA	Cadillac DTS, Cadillac DTS, Cadillac STS, Cadillac XLR, Chrysler 300C.
Japan	Honda Legend, Honda Acura RL; Nissan Infiniti M, Nissan Infiniti Q45, Nissan Primera T-Spec Models, Toyota Lexus LS430/460, Toyota Lexus ES-350, Toyota Sienna XLE, Toyota Avalon.

though some do not clearly understand how it operates and how helpful it is. In this phase, the technical problems have almost been fixed; governmental, industrial and academic entities are transferring their focus from technical issues to marketing and legal issues [7], which will be introduced in detail in the following sections. Until now, most automakers have made ACC systems available in their luxury vehicles, with a trend towards extending this feature from high-end vehicles to mid-range vehicles [6,7]. Most of the ACC-equipped vehicles from 1995–2008 are listed in the Table 3 [7,108].

4. Human perspective analysis

Naturally, automatic systems that assist or replace human operators in safety-critical tasks should comply with the human-centred design principle. Thus, not only the technological capabilities of sensors and actuators but also the autonomy, capabilities and preferences of human operators should be taken into account during the design and implementation processes [109]. Intuitively, ACC systems are typically automatic systems that assist drivers in regulating velocity and following distance. Hence, apart from technical issues, human issues (such as driver behavior, user acceptance and human–machine issues) should be given more attention before ACC systems are introduced into the market. Unlike technical research, researchers usually apply different self-report questionnaires as an effective complementary method to determine the different needs and different driving styles of different drivers of different ages and with different driving behaviours [110,111]. For instance, Hoedemaeker [110] reported the results of a questionnaire study about the needs and driving styles of Dutch car drivers that showed that drivers differ in their needs and motivations regarding driving and also in their driving styles. Rudin-Brown [111] applied three questionnaire studies (the driving internality–externality scale, sensation-seeking scale and baseline trust-in-ACC Scale) to classify participants' psychological needs and driving styles.

4.1. *Driver-behaviour issues analysis*

ACC systems are proposed as an effective way to improve driving comfort by helping with some routine longitudinal driving tasks (such as maintaining a steady headway and keeping a fixed speed), which are assisted or replaced by the ACC system in most traffic situations [4–6]. However, it is not intended for drivers to lose control of and responsibility for their vehicles; they still retain their role as a supervisor to monitor the performance of the ACC system, to observe the real traffic situations and to judge when and whether or not to take over from the ACC system, especially to take control of a vehicle in a situation that an ACC system cannot deal with adequately [112]. Naturally, drivers still retain lateral driving tasks. Most researchers and automotive industry participants consider ACC systems to improve driving comfort by reducing physical workload and driving errors [4–6,113]. Based on the simulator study, Stanton and Yong [114] applied psychological methods to determine whether workload is reduced based on six psychological variables (i.e., locus of control (LOC), trust, workload, stress, mental models and situation awareness [115]). They concluded that LOC and trust were unaffected by the ACC system, whereas situation awareness, workload and stress were reduced by the ACC system. Moreover, based on a field test study, Fancher et al. [116] combined human psychological factors, vehicle dynamics and control theory to evaluate an ACC system and obtained similar results. However, some researchers have different concerns. They believe that ACC systems require driver supervision and judgement, which could increase the mental workload of driving [5,117].

Driving behaviour will definitely change from the normal driving styles when applying an ACC system. Hence, determining how drivers adapt their driving behaviours to acclimate to an ACC system is a very important topic that has already been given a lot of attention by researchers. Despite the fact that ACC systems can provide many benefits for drivers, some negative behaviour adaptations could occur as a result of broadly applying or excessively relying on ACC systems, such as increasing reaction times in safety-critical situations [118–123], and decreasing observation of the minimum time headway in deceleration scenarios [120]. Nilsson [121], who is supported by the Swedish DALTM project, found that in safety-critical situations, drivers tended to wait for the ACC system to respond before reacting, while Kopf and Nirschl [122] at BMW found an increase in reaction times under similar situations from 2–2.3 s to 2.7 s. Another investigation used a full-scale driving simulator that confirmed the above results by measuring the driver's reaction time, magnitude of brake and steering input, and distance between vehicles [123]. Furthermore, negative behaviour adaptations could lead to a failure to reclaim control of the vehicle in situations the ACC system cannot handle appropriately. By applying the simulator, Stanton et al. [124] studied driving workload and the ability to reclaim control from the ACC system in a dangerous scenario. Their results showed that a third of the participants were unsuccessful in reclaiming control of the vehicle before a collision occurred due to a loss of vigilance and an over-reliance on the ACC system. To minimise these negative behavioural adaptations, the researchers [113,114,123,124] suggested as a potential preventive strategy educating drivers on the capabilities and limits of ACC systems and the dangers of blind reliance on these systems and training drivers on situational awareness when using an ACC system.

4.2. *User-acceptance issues analysis*

It may seem that this topic is not necessary because ACC systems have been available on the market since 1995. However, to improve the usage rate and market penetration of ACC systems, user-acceptance issues (such as user-driving acceptance and user-marketing acceptance) still deserve further investigation [125].

User-driving acceptance refers to whether or not drivers are satisfied with or trust ACC systems. Hoedemaeker [126] performed a questionnaire study and two experiments using a driving simulator to access different users' driving acceptances of an ACC system. The results showed that high-speed drivers like the comfort of an ACC system, whereas low-speed drivers like the system's usefulness. Additionally, by applying a driving simulator, Nilsson [121] found that participants driving with an ACC system spent more time in the left lane than participants driving without an ACC system. Evidence for user-driving acceptance of ACC systems also came from a field operational test by Fancher's group [64–66]. This project evaluated the responses of 108 drivers who used an ACC system for a period of 2 or 5 weeks in their natural driving environment. A large data set of driver behaviours was collected that indicated when drivers used the ACC and how they used the ACC in conjunction with manual driving. More evidence for user-driving acceptance of ACC systems came from a Deployment of Interurban ATT Test Scenarios (DIATS) stated preference study [127]; in this study, the priority situations for using an ACC system were found be the following: driving in fog, driving at night on an unlit motorway, driving for 4 h instead of 1 h, driving in low-density traffic, driving at night on a well-lit motorway and driving on an unknown road network.

User-marketing acceptance deals with what kind of people will pay for ACC systems and what kind of price will be accepted by potential users. The stated preference survey from the DIATS project [127] found the following groups of people to be more interested in ACC systems: people describing the way they drive as ‘careful’, people with children under the age of 15 in their household, people who are 50 years old or more, people with an automatic gearbox on their ‘reference car’ and people who say that they do not often change lanes when driving on a highway. This may imply that more careful drivers, who are likely to select larger time-gaps, are more likely to buy and use an ACC system. During an investigation of the driver behaviour adaptation, Rudin-Brown et al. [111] found that drivers with an external locus of control (LOC) were more likely to be willing to purchase an ACC system than drivers with an internal LOC (80% *vs.* 38%). Only a few of the studies have appeared regarding possible purchase prices for ACC systems [118]; the results [65,111,119,128] showed that the acceptable prices range from slightly more than $600 to the highest price of $1000–2000. The reason for the existence of a broad range of acceptable prices is that potential users who are planning to buy luxury vehicles are not sensitive to the exact purchase price of an ACC system. They are more concerned with the comfort and safety of the ACC system. Moreover, the purchase price will gradually decrease as the cost decreases due to higher outputs and advances in technology.

4.3. *Human-machine issues analysis*

According to surveys, driving errors induced by distraction and poor judgement are the major cause of accidents [2,129]. As mentioned above, negative behaviour adaptations could make the problems of distraction and poor judgement worse due to over-reliance and a loss of vigilance [118]; drivers could potentially fail to reclaim control of a vehicle during an emergency scenario due to not clearly understanding the capabilities and limits of ACC systems [118–122]. Apart from educating drivers to minimise these negative effects, more intelligent human machine interfaces (IHMIs) are considered to be another effective way to assist drivers in improving their situational awareness [111,124,130]. The current operation of ACC systems is similar to CCC systems; the common HMI of an ACC system usually includes operational switches, displays, warning devices and pedals (accelerator, brake) [6,24]. However, a number of researchers and automakers have realised that interactions between drivers and ACC systems are not summed up merely by activations/deactivations. They have proposed that more IHMIs be considered as appropriate and feasible preventive features to keep drivers in the control loop [124], allow drivers to completely understand the system’s capability [130] and support the acquisition of situational awareness with a minimum of cognitive effort [111].

However, only a few research results have addressed the framework of an IHMI and how to design an IHMI. The European 5FW RESPONSE project defined six factors that are important for successful interaction between a driver and an active driver-assistance system [7]: perceptibility, comprehensibility, learnability, trust, misuse potential and error robustness. This project also provided guidance for designing the IHMI of an ACC system. Tricot et al. [131] proposed an auto-adaptive HMI system that could operate in many cases (from normal to emergency situations) and that could also adjust its actions to the environment (infrastructure, weather and traffic situations) and to the driver (driving style, workload, stress, state of vigilance and aggression sensibility). Piechulla et al. [132] proposed an adaptive HMI system to reduce the driver's mental workload by filtering the presentation of information according to situational requirements; they implemented such a filter as a projective real-time computational workload estimator based on an assessment of traffic situations by an on-board geographical database. Serafin [133] applied computer-simulated ACC experiments to determine the driver's preferences with respect to adjustable distance control labels for an ACC system. A driving simulator study was conducted by Stapleford et al. [134] to develop possible guidelines for designing and positioning the visual interface of an ACC system.

5. Traffic perspective analysis

Current road transportation systems in most major cities across the world are overburdened and operate inefficiently. Mobility is declining, congestion is rising and safety remains a serious problem [67]. Building additional highways in areas already overbuilt and crowded is no longer a viable solution. Researchers and governments are finally paying attention to the IVHS, which can provide the whole world with more efficient, comfortable and safer road transportation without building additional infrastructure. ACC systems are an effective way to ameliorate traffic problems and have high expectations from governments, automakers and researchers. Notwithstanding the automakers position that ACC systems are comfort systems, most researchers consider the systems to have traffic safety, capacity and stability benefits [7].

5.1. *Safety issues analysis*

Obviously, traffic safety is among the most important issues to motivate research into IVHS, and it compels governments, automakers and researchers to take strong measures to deal with related issues [2,135]. ACC systems were introduced as comfort systems by automakers and their suppliers; however, investigations dedicated to safety issues have found that ACC systems potentially increase safety. In addition, some researchers have proposed standards or framework to assess the safety benefits of ACC systems or similar systems. Choi and Darbha [136] proposed a three-parameter standard that was demonstrated via a Monte Carlo simulation in an emergency braking scenario. These three parameters include the probability of a collision, the expected number of such collisions and the expected relative velocity at impact. Touran et al. [137] proposed a general framework for safety evaluation of ACC systems in rear-end collisions and developed two collision models that use data and specifications from prototype devices. They also applied a Monte Carlo simulation to evaluate the probability of a collision for a string of vehicles and concluded that ACC systems significantly reduce the probability of a rear-end collision.

It is estimated that 90% of traffic accidents occur due to human error [2,137]; ACC systems are implemented to reduce or replace longitudinal driving tasks in order to reduce human error, and thus the number and severity of traffic accidents [85]. A number of investigations and evaluations of safety issues have been conducted by researchers funded by governments and/or automakers. For instance, a comprehensive and independent effort to evaluate the effectiveness of ACC systems was made in the USA [125]; this work was sponsored by the NHTSA and was conducted under a cooperative agreement between the NHTSA and UMTRI. It concluded that the use of ACC systems was associated with safer driving as compared with manual control and, to a lesser extent, CCC. It also concluded that net safety benefits could be obtained if the system was widely deployed. Another comprehensive safety effect evaluation of ACC systems was conducted in the EU under the project DIATS [138]; this evaluation includes detailed statistical results to demonstrate the effects of the improved safety. Average safety improvements of 8.9%, 6.2% and 29.9% resulted from three different ACC algorithms, TNO, UK and SINTEF, respectively. A data dossier has been assembled of the results of ACC safety assessments; the average safety improvements are 8%, 10%, 20%, 12%, 1% and 4% for six different accident types: lane change, obstacles, rear-end collision with queue, rear-end collision without queue, road departure and others, respectively. More safety-related analyses have been performed by other researchers. Chira-Chavala and Yoo [139] found that a possible 7.5% of fatal and severe accidents could be avoided with the use of an ACC system. This point was reinforced by other findings [90,140] showing that fatal and severe accidents could be significantly reduced by 15–33% at easily achievable penetration rates of 30% when the time headway is less than 1 s, and up to 79% in dangerous braking situations in which the vehicle's deceleration rate is more than $5\,\mathrm{m/s^2}$.

As mentioned above, potential negative behavioural adaptations could reduce the drivers' situational awareness by slowing down reaction times or through overreliance on an ACC system [118–124,139]. As stressed above, researchers and automakers have suggested that negative behaviour adaptations can be decreased or eliminated via preventive strategies (such as driver awareness training and more IHMIs [111,130–132]). Other researchers have recommended additional ways to solve this problem, such as Sanchez et al. [141], who proposed that ACC systems can evolve from a comfort system to an active safety system by implementing new additional functions and safety strategies in order to detect and actuate in case of emergency. Jurgen [28] proposed that improving sensor capacity and/or adding redundant sensors to complement the current sensor capacity are effective ways to improve situational awareness. In fact, potential negative behaviour adaptations are why automakers stress that ACC systems are merely a comfort systems rather than a safety systems [7].

5.2. *Capacity issues analysis*

Although ACC systems are implemented as comfort systems, the main focus of traffic researchers or engineers may be whether ACC systems can improve traffic capacity or relieve traffic congestion. In the recent literature [142–144], preliminary microscopic or macroscopic traffic flow simulations and limited traffic flow field operational tests have attempted to address this issue, but their results are controversial due to differences in their simulation models (e.g. FLOWSIM, Monte Carlo), traffic conditions (e.g. traffic demand, highway layout), system parameters (e.g. time headway, maximum deceleration rate), ACC penetration and driver behaviour.

Some researchers have found that ACC systems could significantly improve traffic capacity in some specified situations, such as in cases with small time headway, high ACC penetration and sometimes without a bottleneck of the applied traffic conditions. Broqua et al. [88] assessed mixed traffic flow characteristics by applying the SPEACS micro-simulator to model a simulated two-lane, 6 km motorway stretch without an on-ramp or off-ramp. With a time headway of 1.0 s, they showed that a significant benefit in traffic capacity could be obtained, with increases of up to 6% and 13% in maximum attainable flow when ACC penetration was 20% and 40%, respectively. Minderhoud and Bovy [145] found that, with small time headway of 0.8 s, an ACC system can increase traffic capacity by up to 12%. Treiber and Helbing [146] reported that when 20% of vehicles were equipped with an ACC system on a section of the A8-East German autobahn, nearly all congestion was eliminated. Even if only 10% were equipped, additional travel time due to traffic jams was reduced by more than 80%. At the same time, other researchers have found that ACC systems had only a small or negligible effect on traffic capacity in some situations, such as in cases of moderate time headway and sometimes under bottleneck traffic conditions. VanderWerf et al. [142] found that traffic capacity can be increased by at most 7% when ACC penetration is in the range of 20% to 60% when a medium time headway of 1.4 s and a single protected highway lane with a ramp-highway junction (consisting of a single-lane off-ramp followed immediately by a single-lane on-ramp) are used. Minderhoud and Bovy [145] found that traffic capacity can increase by 4% with a time headway of 1.0 s, while no large or significant changes or trends were observed for any ACC penetration when a time headway of 1.2 s was used in a common situation, an on-ramp to a two-lane motorway. In contrast, some researchers have found that ACC systems cannot improve traffic capacity substantially in certain situations, such as in cases of high time headway. Broqua et al. [88] identified one significant disadvantage, decreases of 3% and 6% in the maximum attainable flow with ACC penetrations of 20% and 40%, respectively, with a time headway of 2.0 s. Davis [147] showed that an ACC penetration of 10% is insufficient to prevent congestion at velocities of 30 m/s and above; however, congestion is suppressed if ACC penetration is 20%. Similarly, Van Arem et al. [148] found that using a time headway of 1.5 s increases trip time and lowers flow stability (with increased deviation from average speed) compared with the use of a time headway of 1.0 s if ACC penetration is 40%.

In summary, improving ACC penetration is not the only effective way to improve traffic capacity; the increase in traffic capacity with an increase in ACC penetration from 20% to 40% is greater than that with an increase in ACC penetration from 0% to 20%. However, above an ACC penetration of 40%, there are no obvious capacity increases [142]. It is widely recognised that to derive capacity benefits, the time headway must not be too conservative (e.g. >2 s) [85,88,148,149]. However, a small time headway is not appropriate due to safety issues and easily leads to traffic instability [145]. Some researchers have proposed to extend ACC systems to CACCs system by applying vehicle–vehicle communication to enable closer vehicle following (time headway could be as low as 0.5 s) [13–15,142].

5.3. *Stability issues analysis*

There exist three stable specifications that are related to ACC systems: individual vehicle stability, string stability and traffic flow stability. Individual vehicle stability means that the spacing error of ACC-equipped vehicle converges to zero if the preceding vehicle is operating at a constant speed, while the spacing error is expected to be non-zero if the preceding vehicle is accelerating or decelerating [8,150], String stability means that spacing errors and the velocity errors do not amplify as they propagate upstream [8,150,151]. Traffic flow stability means that traffic velocity and density evolution are stable [150,151].

In the design of an ACC controller, the first requirement is to obtain individual vehicle stability, which guarantees that the individual vehicle shows a stable behaviour and the following performance. Individual vehicle stability improves driving comfort by avoiding sudden jerks. Although each vehicle obtains individual vehicle stability, the behaviour of the overall coupled system may not be desirable. Hence, string stability has been proposed to evaluate the performance of a group of ACC-equipped vehicles and to constrain the parameters of ACC controllers. String stability has been studied since the mid-1970s [152,153] and has been broadly considered and investigated. In fact, if an ACC controller cannot guarantee string stability and/or traffic flow stability, traffic safety and congestion may become worse instead of becoming better [18]. A common approach to studying string stability is to examine the transfer function from the range error of the preceding vehicle to that of the following vehicle. If this transfer function has a magnitude of less than one at all frequencies, string stability is guaranteed [18,20,154,155]. However, this common approach does not consider the safety and comfort of passengers, e.g. with respect to collision avoidance and the maintenance of acceptable ride quality. Cook [156] proposed to select control parameters to ensure string stability while satisfying constraints that are imposed by considerations of safety and passenger comfort; he investigated several information frameworks of the controller, such as a single-look-ahead framework, a multiple-look-ahead framework and a bi-directional framework. As mentioned earlier, the CTH spacing policy is applied to ACC controllers by automakers and their suppliers. The reason is that the ACC controller could guarantee string stability with on-board sensors alone, but a constant distance spacing policy could not [38]. However, there is no strong proof to confirm that string stability has been implemented in the first generation of ACC systems.

As with analysis of traffic capacity, different researchers have selected different traffic scenarios, different traffic flow models, different spacing policies and different stability analysis techniques to analyse traffic flow stability, leading to controversy in the results obtained regarding ACC systems. Darbha and Rajagopal [151] first studied traffic flow stability using an aggregated macroscopic traffic flow model for an open stretch of highway with entries and exits. They concluded that the traffic flow equilibrium state was marginally stable when using a linearised stability analysis, but traffic flow was unstable when using spatially discretised stability analysis for the CTH spacing policy. Instead of studying an open stretch of highway, Li and Shrivastava [50] studied a circular highway in order to eliminate the entry and exit effects on the intrinsic stability when considering the CTH spacing policy. Several models (such as the microscopic model, spatially discrete model and spatially continuous model) have been applied and several stability conclusions were obtained, depending on the choice of the aggregating biasing strategy used in abstracting the highway's macroscopic dynamics. Li and Shrivastava also concluded that a particular entry and exit traffic policy can destroy the intrinsic stability of an open stretch of highway. Wang and Rajamani [43] discussed and resolved the mathematical controversy between Darbha and Rajagopal [151] and Li and Shrivastava [50] using a spatially discrete model. They provided an explanation for the discrepancy between the results in Darbha and Rajagopal [151] and Li and Shrivastava [50]. Yi and Horowitz [51] proposed a concept of traffic flow propagation stability to study traffic flow characteristics using a macroscopic model that represents both the spatially biasing strategy and ACC-equipped vehicle dynamics; they applied a wave front expansion technique to build an intrinsic stability criterion using the CTH spacing policy. By considering that traffic flow stability could not always be obtained when applying the CTH spacing policy, Wang and Rajamani [43] then proposed an unconditionally stable spacing policy that guarantees traffic flow stability under all boundary conditions. Santhanakrishnan and Rajamani [157] also proposed an 'ideal' spacing policy that is a nonlinear function of speed known as the variable time headway (VTH) spacing policy. They concluded that the VTH spacing policy can provide string stability and traffic flow stability as well as a higher traffic flow capacity as compared with the CTH spacing policy.

6. Society perspective analysis

Any newly developed technology not only influences people's normal life, but also brings many changes to society. ACC systems have been developed as assistant driving systems to reduce or remove the drivers' longitudinal driving workload; they are considered the first logical step in a progressive path leading to a future automated highway system. Their development and deployment definitely influence people's normal life and bring about many changes to society. Hence, neglecting the analysis of the relationship between ACC systems and society is unreasonable and irresponsible. In this paper, we try to describe this relationship clearly by analysing environmental issues, market issues and legal issues.

6.1. *Environmental issues analysis*

Intuitively, a reduction in traffic congestion and an increase in traffic capacity can benefit the environment. Unfortunately, only a few research studies have addressed this benefit; however, these limited sources have shown that ACC systems actually do benefit the environment by reducing fuel consumption and vehicle emissions. Bose and Ioannou [158–160] proposed that some of the characteristics of ACC-equipped vehicles (such as accurately following a lead vehicle, attenuating position errors that are generated by the lead vehicle during smooth transients and the smooth response for filtering out traffic disturbances that are caused by rapid acceleration transients) could benefit air pollution and fuel consumption. They applied the comprehensive modal emissions model and Pipes human driver vehicle following model to simulate and confirm their ideas. Simulations and limited field operational tests demonstrated that fuel consumption and air pollution levels can be reduced during rapid acceleration transients by 28.5% and 60.6%, respectively, if ACC penetration is 10%. Zhang and Ioannou [161] and Ioannou et al. [162] compared two ACC systems to demonstrate which features or characteristics benefit the environment. In their reports, the terms ACC01 and ACC02 referred to two different ACC systems. The ACC01 system is a normal ACC system with normal characteristics. The ACC02 system treats the vehicle following task as a special speed tracking task and incorporates more intelligence in dealing with disturbance rejection, smooth response and safe vehicle following without affecting travel time. The ACC02 system provides better transient performance than the ACC01 system and can attenuate oscillations in the speed response of the preceding vehicle. Comparative simulations showed that the ACC02 system provides better fuel economy and vehicle emission results than the ACC01 system. This comparative research indicates that a smoother response and fewer position errors can lead to better fuel economy and vehicle emissions.

6.2. *Marketing issues analysis*

In comparison with the issues described above, the marketing issue is the most important focus of automakers and their suppliers. Before the broad deployment of ACC systems, all automakers and their suppliers must conduct marketing investigations and analysis to reduce potential investing risk. Unfortunately, only a few of these investigations and reports have been published as they are considered commercial secrets. However, automakers have declared that consumers highly value ACC systems as a significant stress-reliever when driving in highway traffic and would be willing to pay for it [65,111–113,117,118,127,139]. Ervin et al. [163] of the University of Michigan Transportation Research Institute conducted a pre-market investigation of ACC systems. They applied an interview method to determine the auto industry outlook on ACC systems, with special emphasis on the North American market. Both suppliers and OEM companies were questioned on their expectations for product feature requirements, preferred technologies, institutional issues, management strategy and marketing. The results showed that ACC systems will be marketed on luxury cars first, that most of the products will use radar as the range sensor, that the driver will have a means to adjust the headway time and that the common entry price will be around $1000 (although different feature may cause the price to vary considerably). The major source of technical uncertainty is in the ranging sensor, although uncertainties also exist in terms of the functional features that will minimize liability risk while providing suitable utility for customers. Although there are few referenced studies related to the marketing of ACC systems, there is sufficient marketing research and analysis for ADAS [7,164–166]. In addition, a wide-range societal impact analysis has been conducted by many of the European projects, including CARTALK, AWAKE, ADASE2 and RESPONSE2. These projects were financed by public funding and governments to provide government policy-makers with a broad perspective on how ADAS will fit within the larger society. The findings of these projects apparently could provide useful suggestions to automakers when developing their marketing strategies.

Although we could not obtain many resources regarding the marketing of ACC systems, we could ascertain that the first generation of ACC-equipped vehicles was available on the market in Japan in 1995, in Europe in 1998 and in North America in 2000 [7]. In late 2004, the low-speed stop-and-go ACC (S&GACC) system was introduced to the Japanese market by Nissan and Toyota [7]. Most automakers across the whole world (such as Audi, BMW, DaimlerChrysler, Fiat, GM, Honda, Jaguar, Nissan, PSA, Renault, Saab, Toyota and Volkswagen) have made ACC systems available in luxury vehicles, while some automakers have extended this feature from high-end vehicles to mid-range vehicles (such as the Nissan Primera and the VW Passat in Europe and the Sienna minivan in North America [7,108]).

6.3. *Legal issues analysis*

As mentioned above, ACC systems can potentially improve the safety of road traffic (especially highway traffic), but they definitely cannot prevent traffic accidents. ACC systems can replace a driver's longitudinal driving work and can also change the driver's driving style to some degree; thus, they may change the characteristics of traffic accidents. Therefore, there is the possibility that the introduction of ACC systems could shift the liability distribution from drivers to automakers. This is why automakers and their suppliers stress that ACC systems are comfort systems rather than safety systems. This is also the reason why they have slowed the introduction of the low-speed S&GACC system, the full speed ACC system and a more advanced system that integrates an ACC system with a collision warning/avoidance system.

As with marketing, there are no publications that discuss the legal issues of ACC systems. The available research publications have instead investigated and analysed the legal and institutional issues related to the AHS and IVHS in the USA [167–169] and the ADAS in Europe [170–172]. However, these findings are applicable to ACC systems because ACC systems are usually considered to be the first logical step in a progressive path leading to a future AHS or IVHS [7]. Syverud [167] briefly discussed the current US legislation for traffic accidents and subsequent lawsuits [5]. He found that most of the liability costs of the accidents are paid by car owners through their own liability insurance, but he also pointed out that IVHS technology might shift the liability distribution towards the manufacturer or highway owners, who are responsible for intelligent highway systems. Syverud then proposed techniques to manage liability risk and reduce liability costs for automakers. Chen and French [168] provided a more detailed account of the organisational response to the IVHS and the introduction barriers that exist. They also reviewed the structure of the organisational activities across Europe, US and Japan towards materialisation of the IVHS. Costantino [169] and Khasnabis et al. [173] looked into other legal and institutional barriers and government liability with respect to the development of an IVHS and AHS primarily from a governmental point of view. They analysed the practical measures that can be taken by the government to exempt government agencies from lawsuits in IVHS-related accidents without undermining the interests of citizens or discouraging private investment. In the USA, liability concerns typically delay market introductions by 2 or 3 years, which is why ACC systems were introduced into the US market behind the Japanese and European markets.

The above-mentioned discussions were within the context of the United States legal system, so some of the research results are not fully applicable to Europe. European public funding and private organisations have supported similar studies of legal issues under the European legal system to determine how to introduce the ADAS into the market without legal barriers. An initiative is underway in Europe that is focused on a worldwide CoP for the design and testing of ADAS to significantly impact the industry in managing the liability risk and reducing liability costs [7,170–172]. Van der Heijden and Van Wees [171] analysed whether current legislation frameworks can accommodate the smooth development and market implementation of the ADAS. They concluded that the current legal frameworks in both the fields of vehicle safety standards and liability provide for (some) flexibility towards technical developments regarding ADAS. However, public tensions between innovation and safety resulting from the introduction of the ADAS will generate public and private interventions that require preventive safety standards. Van Wees and Brookhuis [172] further proposed that the potential liability of the system's developers and car manufacturers is often considered a barrier for the rapid deployment of ADAS. The European Product Liability Directive's concept of a defective product is described and analysed from both legal and human factor perspectives. In legal debates concerning product liability, two different approaches based on consumer expectations and risk-benefit analysis can be distinguished. Van Wees and Brookhuis also argued that although product liability can slow the pace of introduction, it can prevent an immature or poorly designed ADAS from entering the market.

7. Summary

ACC systems are considered to be an extension of CCC systems and are implemented to reduce or remove longitudinal driving work on the highway by automatically keeping a user-set speed or user-set time headway between the ACC-equipped vehicle and the preceding vehicle in the same lane. Its success could be considered a good example of the design, implementation and deployment of an ADAS with the complete cooperation of governmental, academic and industrial entities. For instance, projects of PROMETHEUS, DRIVE, Mobility 2000, ITS America, VERTIS and AVS have been successfully conducted by working together. Due to controversies regarding the benefits with respect to driving safety and traffic capacity, automakers and their suppliers have claimed since their introduction to market in 1995 that ACC systems are merely driving assistant systems that improve driving comfort. To improve driving safety and traffic capacity beyond doubt, some researchers have proposed advanced ACC systems, such as stop&go, full speed and cooperative ACC systems [173]. Some researchers have further proposed to update and advance ACC systems to active safety systems or predictive safety systems by applying low-cost, high-performance distance sensors and an active braking system [141,174]. To some extent, the potential for legal risk is a barrier to improving ACC penetration and to deploying the next generation of ACC systems or similar driving assistant systems. Actually, this nontechnical issue is much more complicated than the technical issues and demands much closer cooperation from governmental, academic and industrial entities than do the technical issues. In short, the people deserve safer, more comfortable and more efficient vehicle, and they will get it.

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