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J. Piao[a]; M. McDonald[a]
[a] Transportation Research Group, School of Civil Engineering and the Environment, Southampton University, Southampton, UK

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Advanced Driver Assistance Systems from Autonomous to Cooperative Approach

J. PIAO and M. MCDONALD

Transportation Research Group, School of Civil Engineering and the Environment, Southampton University, Southampton, UK

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ABSTRACT *Advanced Driver Assistance Systems (ADAS) have been one of the most active areas of ITS studies in the last two decades. ADAS aim to support drivers by either providing warning to reduce risk exposures, or automating some of the control tasks to relieve a driver from manual control of a vehicle. ADAS functions can be achieved through an autonomous approach with all instrumentation and intelligence on board the vehicle, or through a cooperative approach, where assistance is provided from roadways and/or from other vehicles. In this article, recent research and developments of longitudinal control assistance systems are reviewed including adaptive cruise control, forward collision warning and avoidance, and platooning assistants. The review focuses on comparing between autonomous systems and cooperative systems in terms of technologies used, system impacts and implementation. The main objective is to achieve common understanding on ADAS functional potentials and limitations and to identify research needs for further studies.*

Introduction

A rapid growth has been seen worldwide in the development of Advanced Driver Assistance Systems (ADAS) because of improvements in sensing, communicating and computing technologies. ADAS aim to support drivers by either providing warning to reduce risk exposure, or automating some of the control tasks to relieve a driver from manual control of a vehicle. From an operational point of view, such systems are a clear departure from a century of automobile development where drivers have had control of all driving tasks at all times. ADAS could replace some of the human driver decisions and actions with precise machine tasks, making it possible to eliminate many of the driver errors which could lead to accidents, and achieve more regulated and smooth vehicle control with increased capacity and associated energy and environmental benefits.

Correspondence Address: J. Piao, Transportation Research Group, School of Civil Engineering and the Environment, Southampton University, Highfield, Southampton SO17 1BJ, UK. Email: jpiao@soton.ac.uk

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ADAS functions can be achieved through an autonomous approach with all instrumentation and intelligence on board the vehicle, or through a cooperative approach in which assistance is provided from roadways and/or from other vehicles. Although many studies have been reported about the development of ADAS systems (Risack *et al*., 2000; Venhovens *et al*., 2000; Marsden *et al*., 2001; Cotter *et al*., 2006), few attempts have been made to compare the autonomous and cooperative approaches in terms of technology capability, systems functions and implications of the system implementation. In this article, recent developments of autonomous and cooperative ADAS systems, particularly longitudinal control assistants, are reviewed. The main objective is to achieve a common understanding of functional potentials and limitations of ADAS systems from different approaches and to identify research needs for future studies.

Section 'Autonomous and Cooperative Approach' of the article provides an overview of current developments in autonomous and cooperative ADAS systems. Efficiency and safety impacts of cruise control assistants using different approaches are described in Section 'Cruise Control Assistants'. Analysis of functional and technical feasibilities of autonomous and cooperative collision warning and avoidance systems are presented in Section 'Collision Warning and Avoidance', which is followed by a discussion of legal issues with autonomous and cooperative ADAS systems. Finally, implementation issues relating to ADAS systems as well as future research needs are discussed in Section 'ADAS Implementation'.

Autonomous and Cooperative Approach

Autonomous Systems

Autonomous ADAS systems use on-board equipment, such as ranging sensors and machine/computer vision, to detect surrounding environment. The main advantages of such an approach are that the system operation does not rely on other parties and that the system can be implemented on the current road infrastructure. Now many systems have become available on the market including Adaptive Cruise Control (ACC), Forward Collision Warning (FCW) and Lane Departure Warning systems, and many more are under development.

Currently, radar sensors are widely used in the ADAS applications for obstacle detection. Compared with optical or infrared sensors, the main advantage of radar sensors is that they perform equally well during day time and night time, and in most weather conditions. Radar can be used for target identification by making use of scattering signature information (Ramzi, 2003). The range accuracy of simple pulse radar depends on the width of the pulse it transmits, which has a trade-off with the bandwidth requirement of the receiver and transmitter. Creating a sufficiently large angular reach with correspondingly good angular resolution is one of the key issues with radar-based sensors (Agogino *et al.*, 2000).

Unlike radar sensors, laser sensors have the potential for a larger angular reach and a better angular resolution (especially with a scanning principle) than radar-based sensors; this is particularly useful for risk detection in an environment with pedestrians and cyclists such as an urban street (Osungi *et al*., 1999; Venhovens *et al*., 2000). The main disadvantage of laser sensors is that they are very sensitive to adverse weather conditions, for example rainy weather, which could result in reductions of detection range and create 'ghost' objects due to road spray.

Machine vision is a simple mode of computer vision (without much image processing required). It is widely used in ADAS for supporting lateral control such as lane departure warning systems and lane keeping systems (Seger *et al.*, 2000). Currently computer vision has not yet gained a large enough acceptance in automotive applications. Applications of computer vision depend much on the capability of image process and pattern recognition (e.g. artificial intelligence). The fact that computer vision is based on a passive sensory principle creates detection difficulties in conditions with adverse lighting or in bad weather situations (Venhovens *et al.*, 2000). A large amount of information is available and isolating the features of interest and extracting the necessary information is not straightforward. The high cost coupled with a computer vision system might only be justified if additional functions could be realized with this type of sensor.

Sensor fusion can be used as a complementary device for vehicle detection. Several studies have been reported on their applications including Hofmann *et al.* (2001), Steux *et al.* (2002), Ramzi (2003) and Sole *et al.* (2004). Sensor fusion for vehicle detection can be achieved at different levels to meet different requirements of ADAS applications, for example, combining several sources of raw data to produce new raw data that combines various features such as edges, corners, lines, texture into a feature map (Hofmann *et al.*, 2001; Sole *et al.*, 2004).

Differential Global Positioning System (DGPS) is a technology which has attracted great interest in vehicle positioning. The standard accuracy of GPS position estimates is currently in the order of 20 m. Increased accuracy (at the metre level) can be achieved through the use of DGPS (Parkinson and Spilker, 1996; Farrell and Barth, 1999). Furthermore, a DGPS system that uses integer-resolved carrier phase observations can provide accuracy of 1–3 cm (Farrell *et al.*, 2003). For vehicle control, a trajectory corresponding to the desired path can be defined in the global coordinate reference frame and stored on board the vehicle. An approach to integrate an Inertial Navigation System (INS) and a DGPS has been studied on several occasions (Farrell *et al.*, 2003; Ryu and Gerdes, 2004). Inertial navigation has been widely used in air, land and sea application systems (Parkinson and Spilker, 1996; Farrell and Barth, 1999). A typical INS system integrates the differential equation describing the system kinematics for a short period of time using high-rate data from a set of inertial instruments. During this integration process, the error variance of the navigation state increases primarily due to sensor noise and errors in sensor calibration and alignment. An INS system used in conjunction with aiding sensors can provide the full state estimate at the desired control frequency more accurately than either technique used individually. In addition, the INS would continue to provide position estimates at times when signals from the aiding sensors were not available. Currently, GPS has been applied in vehicle navigation and Electronic Toll Collection (ETC) to provide location references (Catling, 2002). With the improvement in accuracy of vehicle positioning, GPS has the potential to be used for vehicle control applications such as ACC (Baum *et al.*, 1997; Gallet *et al.*, 2000) and collision warning and avoidance systems (Jocoy and Pirson, 1999; Oloufa and Radwan, 2001).

Currently, most autonomous systems are developed by vehicle manufacturers for increasing competitiveness of their products. Nearly all of the big manufacturers have schemes to promote the research and development of the systems. Sensor technologies can become much more sophisticated to improve the performance in vehicle detection; however, they only regard threats within the immediate vicinity of the equipped vehicle. For example, a radar-based ACC can only detect a preceding vehicle within the operative range of the sensors. Therefore, applications of such systems are limited.

Cooperative Systems

With a cooperative approach, individual vehicles relate to the environment by communication with other individual vehicles or road infrastructures, or through detection of specifically designed infrastructure features (Burton, 2004). Unlike development of autonomous systems which are mainly driven by car manufacturers, cooperative systems make it possible for wide and balanced interests, such as safety and efficiency, to be considered in the development and implementation of the systems.

Although the concept of cooperative driving started with the advent of Intelligent Transport Systems (ITS) in the 1980s, large-scale research and development of cooperative systems has only materialized in recent years. In Europe, early research on applications of inter-vehicle communications was undertaken in the PROMETHEUS project (Augello, 1991), where a 57 GHz inter-vehicle communication system was developed to achieve cooperative driving. In the CHAUFFEUR project (Bonnet and Fritz, 2000), an electronic tow-bar system was developed for trucks to follow each other with short spacing, in which vehicle-vehicle communication was used to transmit deceleration information from the leading vehicle to the following vehicles to ensure string stability. In the European Project CarTALK 2000 (Morsink *et al.*, 2002), one of the main objectives was to develop cooperative driver assistance systems using inter-vehicle communication. Cooperative Vehicle-Highway Systems (CVHS) was a UK government supported project to promote the development of cooperative systems (Crawford, 2003), where business cases for the implementation of different cooperative system options were studied based on cost/benefit analysis. Currently, several European projects are ongoing which are focused on the development of cooperative systems including CVIS, COOPERS and SAFESPOT, three integrated projects which are funded by European Commission under the 6th Framework Programme. The CVIS project aims at defining high-level architecture and developing a platform to allow vehicles to communicate and cooperate directly with other nearby vehicles and with roadside infrastructures. The COOPERS project focuses on developing a cooperative system which is based on communication between road infrastructure and vehicles. The SAFESPOT project focuses on applications of inter-vehicle communication to increase road safety.

In the USA, the Cooperative Vehicle-Highway Automation Systems (CVHAS) project was a federal programme initiated in 2000. The systems aim to provide driving control assistance or fully automated driving, based on information about the vehicle's driving environment, which is obtained by communication from other vehicles or from the infrastructure, as well as from their own on-board sensors. The Infrastructure Consortium was established in June 1999 in response to a request by the U.S. DOT's ITS Joint Program Office to transform the focus of the hitherto named 'Speciality Vehicle Consortium' from snow removal (and some emergency vehicle) to the more general class of vehicle-highway cooperative systems. Vehicle Infrastructure Integration (VII) programme is a cooperative effort which is based on work previously done in the Intelligent Vehicle Initiative; the VII initiative is to work towards deployment of advanced vehicle-vehicle and vehicle-infrastructure communications that could improve road safety (Farradyne, 2005; Mahoney, 2005).

In Japan, research on cooperative systems started from automated highway systems although the focus of the research was changed in the mid-1990s to 'Advanced Cruise-Assist Highway Systems' (AHS). This change in focus was coupled with the formation of a public-private partnership of Advanced Cruise-Assist Highway Systems Research Association (AHSRA) and focuses on infrastructure-based sensing and intelligence for collision warning and avoidance, with communication from infrastructure to vehicles (Satoshi *et al.*, 2002). AHSRA defined three levels of development of cooperative systems: AHS-i (information to the driver), AHS-c (control assist for the driver) and AHS-a (fully automated operations). Some of the results were demonstrated at 'SmartCruise21' Demo 2000 (Tsugawa *et al.*, 2001) with focus being almost entirely on the use of infrastructure-based sensing and communication devices. Super-Smart Vehicle Systems (SSVS) is another main programme devoted to the development of cooperative systems. The focus is on the use of DGPS and vehicle-vehicle communication for coordination of vehicle control. It aims at improving the safety, comfort and efficiency of motor vehicle traffic by adding sophisticated functions such as environment recognition and danger avoidance functions, travelling information exchange functions and traffic flow control functions. Some of the systems were demonstrated in SmartCruise21 Demo 2000 (Tsugawa *et al*., 2001).

Vehicle-vehicle communication. With vehicle-vehicle communication, a group of equipped vehicles forms a temporary network which is linked together by a wireless ad hoc communication network. One of the main advantages of vehicle-vehicle cooperation is that information and data otherwise difficult or impossible to measure directly through on-board 'sensors' (e.g. braking capacity of the preceding vehicle) can be collected through such inter-vehicle communication.

One potential application of inter-vehicle communication is to relay hazard information from a preceding vehicle to following vehicles, in an effort to prevent multi-vehicle accidents, particularly when in condition of poor visibility (Jin and Recker, 2006). Inter-vehicle communication can also be used for an on-board sensor equipped vehicle to transmit relevant information to non-equipped vehicles (e.g. road surface information such as coefficient friction to following vehicles), as studied in German-French IVHW project and EU WILLWARN project (a subproject of PReVENT). Furthermore, inter-vehicle communications can be used for transmission of movie data among the vehicles which allows creation of a 'virtual cabin' of the partner vehicle in one's own vehicle (Kato *et al.*, 2000; Tsugawa, 2005).

For in-vehicle communication to support longitudinal control, one of the key requirements is regular and constant information transmission from a leading vehicle to its immediate following vehicle regarding its current speed, acceleration/deceleration, braking capability and loading status, etc. Applications of inter-vehicle communication make it possible to adapt longitudinal control to the traffic in front and allow anticipating early braking manoeuvre when an invisible vehicle in front is braking. Such functions have been studied in research projects such as CarTALK 2000 project (de Bruin *et al.*, 2004). Inter-vehicle communication can also be used to achieve platooning where vehicles follow each other with short spacing, as demonstrated in Demo 1997 (Ozguner *et al.*, 1997), Demo 2000 (Tsugawa *et al.*, 2001) and CHAUFFEUR project (Bonnet and Fritz, 2000).

Inter-vehicle communication has also shown great potential to improve performances of active safety systems. With inter-vehicle communication, forward collision warning and avoidance systems can transmit an emergency braking message to its following vehicles, resulting in reduced response time as studied in US VSCC (Tsugawa, 2005). For collision warning at intersection, a vehicle can send GPS data to other vehicles through inter-vehicle communication to make them aware of approaching vehicles which are beyond their range of view (Misener and Sengupta, 2005). Other applications include providing lane change and merge assistance where vehicles are aware of each other's position through inter-vehicle communication, as demonstrated in Demo 2000 (Tsugawa *et al.*, 2001).

Although much research and development work has been carried out, there are no practical inter-vehicle communication systems in operation currently. One of the main challenges is to develop a wireless communication technology which is capable of providing a high-performance, highly scalable and secure service to ensure good quality of communication between vehicles in a dynamic and mobile network (Liu *et al.*, 2005).

Road-vehicle communication. Road-vehicle cooperation can be achieved through many approaches such as detection of specifically designed infrastructure and road-vehicle communication. Using magnetic sensors to read road markers was demonstrated in Demo 1997 in which magnetic plugs were embedded along the road so that a vehicle knows its longitudinal and lateral position. This technology can work at high speed as shown in the Automated Highway System demonstration (Quinlan, 1998). Other information relating to downstream road conditions (e.g. road shape, curvatures) can also be passed to vehicles by encoding with the magnetic plugs on roads. This technology has been used in vehicle guidance applications such as Phileas automated vehicles (Stauffer, 1995; Siuru, 2004).

Road-vehicle communication makes it possible for road operators to provide drivers with dynamic information such as road surface condition, traffic condition and weather conditions. Such communication could be applied in a one-to-many mode, i.e. by broadcasting to provide general information to all the vehicles in the communication area, or in a one-to-one mode to provide relevant information to individual vehicles. Communication can be one way (e.g. from roadside to vehicle) or two way (e.g. with vehicles being taken as mobile sensors to collect traffic data) which depends on the purpose of the applications.

For road-vehicle communication, one of the options is Dedicated Short Range Communication (DSRC) which has been accepted as a communication standard dedicated to road telematics applications. Currently, DSRC has already been used in some ETC applications (Catling, 2002; Staudinger, 2005). With the platform of road-vehicle communications, other services can also be provided to drivers, for example dynamic navigation and traffic information (Belarbi *et al.*, 2001).

Cruise Control Assistants

The Challenges

Adaptive Cruise Control aims at relieving a driver from manually adjusting his/her speed to achieve a safe cruise driving. When driving in free traffic, the system holds a preset speed, like a conventional cruise control system, and when following another vehicle, the system automatically maintains a desired time gap from the preceding vehicle (Fancher, 1998). To achieve ACC function, the following are required:

- the system is able to constantly obtain kinematics information of the preceding vehicle including relative distance and relative speed to the host vehicle;
- availability, accuracy and reliability of the data under various conditions (e.g. weather); and
- the driver is allowed to take over the control whenever needed (e.g. does not feel safe to use it).

Stop&Go can be seen as a typical evolution of ACC which aims to support cruise control at low-speed driving with the capability of automatic start and/or stop (Venhovens *et al.*, 2000). Driving with Stop&Go can relieve a driver from frequent accelerations and brake operations, which therefore has great potential to increase driver comfort in congested traffic. However, unlike an ACC system, where only a moving vehicle is taken into account, a Stop&Go system has to detect both moving and stationary objects on its driving path to ensure safety. To operate a Stop&Go system in urban traffic conditions, the system will pay attention not only to the vehicle in front, but also to other road users (e.g. pedestrians, cyclists, mopeds, vehicles); therefore, the detection and control requirements are much more stringent than those for ACC.

As a system to enhance driving comfort/convenience, the braking capacity of an ACC and Stop&Go is limited (e.g. -3 m/s^2), and the driver has to take over the control in situations when a higher level of braking is needed, for instance, an emergency braking. To achieve ACC and Stop&Go functions, one of the key tasks is to detect the presence of a vehicle in front. This can be realized through an autonomous approach, for example by using ranging sensors, or through a cooperative approach, for example by using vehicle-vehicle communication.

Sensor-based systems. Ranging sensors (e.g. radars or lasers) are often used to measure the range and range rates to the preceding vehicle. Most of the current ACC systems are developed for highway operation and automatically switch off when driving at lower speed, e.g. 30 km/h. Many car makers, e.g. BMW, TOYOTA and NISSAN, are working to further enhance their cruise control systems by providing Stop&Go function which makes it possible to extend the operation speed range all the way to a standstill. For example, the ACC long-range radar (e.g. 120 m operation range) is supplemented by an additional close-range radar sensor to measure the distance, lateral position and relative velocity of the vehicle ahead (e.g. 20 m).

The second generation of radar sensors is under development (Ramzi, 2003). Compared to the current radars, higher resolution and increased sight angle will become possible. They will allow the system to closely monitor a major part of the road ahead. This means that the preceding vehicle can be tracked for a longer period of time in narrow curves and on entry and exit slips of motorways. This also makes it possible to combine ACC and Stop&Go functions based on a single radar sensor, unlike current systems where separate radars have to be used to detect objects located in different ranges.

Radar-vision fusion is another approach which is being studied to improve vehicle detection. Such an approach can increase reliability and accuracy of vehicle detection from different sources of sensor measurement which are often complementary in function. For example, Hofmann *et al.* (2001) studied a Hybrid Adaptive Cruise Control (HACC) that was a combination of a radar and visual perception. Their results showed that an enhanced robustness is achieved by cooperative estimation of egomotion and the dynamics of other vehicles.

Currently Stop&Go systems are mainly used for highway operation. The system can automatically bring the vehicle to stop, but the driver has to start the vehicle manually. Although being attractive to many drivers, Stop&Go systems with full functionality of automatic 'stop' and 'go' are not yet available on the market. There are many issues to be resolved for introducing such systems, including both technical and liability issues. To run Stop&Go with automatic 'go' functions, manufacturers may become liable if an accident occurs (more detailed discussions about liability issues of ADAS can be seen in Section 'Legal Issues').

From an operational point of view, sensor-based ACC and Stop&Go systems may cause some difficulties for other vehicles during merging or lane changing, especially in situations when a large number of vehicles are equipped with the system. If any driver makes a cut-in into the gap, it would pose serious threats to the following vehicle as the braking capacity of cruise control assistants is not large enough to deal with emergency braking (Fancher, 1998; Minderhoud and Bovy, 1999; Misener *et al.*, 2002).

Cooperative systems. Another approach to realize cruise control is through vehicle-vehicle communication. With such an approach, current speed and acceleration of the preceding vehicle can be transmitted to the following vehicles by inter-vehicle communication. In European Project CarTALK 2000 (Morsink *et al.*, 2002), one of the main objectives of the project was to develop cooperative driver assistance systems and a self-organizing ad hoc radio networks as a communication basis. Unlike sensor-based ACC, communication-based systems may anticipate early braking manoeuvres when an 'invisible' vehicle in front is braking. This leads to a more natural following behaviour (MacNeille and Miller, 2004).

With vehicle-vehicle communication, ACC and Stop&Go functions can be combined into one single system which is able to work at all speed ranges. In addition, they have the potential to integrate with other functions such as merging and lane changing assistance which are based on negotiations between vehicles (via vehicle-vehicle communication). One of the main disadvantages of the systems is that both the proceeding and the following vehicles have to be equipped. In addition, a separate technology has to be used to get spacing information from the preceding vehicle, for example by using GPS plus digital road maps (as tested in CarTALK 2000 project).

Despite a high degree of interest in such a concept, no communication-based cruise control systems are available on the market currently. Most systems are still in prototype stage and many issues need to be resolved including both technical (e.g. reliability of vehicle-vehicle communication) and legal (e.g. who should be blamed if an accident happens: vehicle manufacturers or communication technology providers).

Potential Impacts on Capacity and String Stability

Capacity impacts. Many results have been reported about the potential efficiency impacts of cruise control assistants, particularly for ACC. This includes ICC FOT, one of the largest ACC field operation test undertaken to evaluate ACC impacts

(Koziol *et al.*, 1999). As a comfort system, most cruise control assistants are designed to imitate driver behaviour in selecting inter-vehicle spacing. This means providing a range of spacing options for a driver to select (no very short time gaps, for instance <1 s are allowed). Compared to manual driving, slightly larger spacing is required for ACC driving in order for the driver to have enough time to reclaim the control in an emergency braking scenario (Stanton *et al.*, 1997; Bose and Ioannou, 2001).

Understanding ACC impacts on traffic capacity is of interest to many transport researchers. Many studies have been reported on the traffic impact of autonomous ACC. Minderhoud and Bovy (1999) studied the capacity effects of sensor-based ACC under different assumptions of time gaps and penetration rates. Their results show that the ACC with time-gap setting of 1.2 s would leave traffic flow capacity essentially unchanged from the baseline scenario, while time gaps of 1.0 s and 1.4 s could cause noticeable, but small, increase and decrease in flow capacity respectively at higher penetration rates. VanderWerf *et al.* (2002b) studied ACC impacts on highway flow capacity by Monte Carlo simulation, based on single-lane highway with entry and exit ramps being considered. Under the assumption that average ACC users choose a mid-range time gap of 1.4 s, they found the impacts of ACC seemed to peak at 20% through 60% market penetration. Increasing ACC penetration above 60% may lead to modest loss of highway capacity if ACC users choose a time gap larger than that when driving manually. Based on their simulation results, they concluded that sensor-based ACC can only have limited impacts on highway capacity even under the most favourable conditions. Minderhoud and Bovy (1999) have studied the potential impacts of ACC with short time gaps and found that it is necessary to reduce the time gap of 0.8 s to generate capacity increase in the 10% range at a penetration level of 50% or higher. Similar results have also been reported by Cremer *et al.* (1998) and Zwaneveld *et al.* (1999).

Communication-based systems can be designed to have a shorter reaction time than sensor-based systems, and therefore have the potential to adopt shorter time gaps than sensor-based systems. In a study by VanderWerf *et al.* (2002b), efficiency impacts of ACC (0.5 s time gap) were simulated with the assumption that the system can brake with the maximum rate in emergency braking, which is much shorter than 1.1 s, generally used with manual driving (Carbaugh *et al.*, 1998). Their simulation results show that the gain in capacity increases quadratically with the penetration level: the capacity would be doubled at 100% penetration. This effect is explained by the fact that the reduced time gaps are only achievable between pairs of vehicles equipped with the ACC, the higher the number of equipped vehicles, the higher the chances of cooperation through vehicle-vehicle communication.

There is an issue of user acceptance of close following with ACC. As a comfort system, ACC has a limited braking capacity (e.g. 0.3 g), and the driver has to intervene when higher braking capacity is required, for example in emergency braking. Following another vehicle with short headways would leave little time for the driver to take over control. Ultimately, the minimum safe time gaps between vehicles are dependent on human drivers, rather than the ACC systems. For ACC, there is a broad international agreement that the systems should not be designed to operate with time gaps shorter than 1.0 s (ISO/DIS 15622; VanderWerf *et al.*, 2002b). This means that close following with ACC is technically impossible, unless ACC is combined with other functions such as automatic collision avoidance to ensure safety.

Although many studies have been reported on the efficiency impacts of cruise control assistants, especially on ACC, most of the current results are based on simulation and simulator experiments (Godbole *et al.*, 1999; Bose and Ioannou, 2001; VanderWerf *et al.*, 2002a, b). Although ACC have been introduced to the market, current penetration has not reached the level at which ACC impact can be observed directly to validate efficiency impacts. In order to further understand the true impacts of the cruise control assistants, more research is needed on driver behavioural response in real-time use of ACC including selection of time gaps, when engaging and disengaging with the system.

Platooning has a great potential to increase traffic capacity where vehicles follow each other with short spacing. One of the main control goals of platooning is to maintain a preset distance gap between vehicles. The acceleration of the vehicles in the platoon is determined in a way that string stability and range errors are not increased towards the end of the platoon (Tan *et al.*, 1998; Swaroop and Rajagopal, 1999; Godbole and Lygeros, 2000).

Recent studies on platooning focus on applications for heavy goods vehicles (HGV). One of the key technologies used for such a system was vehicle-vehicle communication which is used to transmit information on acceleration/deceleration from the leading vehicle to the following vehicle. Such capabilities have been demonstrated in the EC CHAUFFEUR project (Baum *et al.*, 2001), where the leading vehicle is driven conventionally, and the following vehicle is towed by an electronic tow-bar (with a fixed inter-vehicle spacing). In the first stage of CHAUFFEUR project, a two-truck platoon was demonstrated successfully; now three or more truck platoons are under development in the second stage of the CHAUFFEUR project (Harker, 2001). For platooning, it is a challenge to get information about the loading status of the vehicle in front and road geometry ahead. The mass of the HGV vehicles varies considerably in different loading scenarios and mild road grades can be a serious loading problem for a heavy vehicle (Olavi and Jussi, 2001; Bae and Gerdes, 2003; Vahidi *et al.*, 2003).

Impacts on string stability. String stability is often used to assess how range errors develop (decrease or increase) as they propagate along the vehicle stream (Kawabe, 2000; Zhou and Peng, 2005). String stability is required in order to avoid amplification of vehicle disturbances from a leading vehicle to the following ones in a traffic stream, for instance, in merging areas, or on a road with significant grades. It is generally believed that cruise control assistants have the potential to improve string stability through more efficient detection of changes in spacing and speed of the front vehicle, leading to more smooth and stable traffic. Several studies have been reported on ACC impacts on string stability (Liang and Peng, 1999; Kawabe, 2000; Yamamura and Seto, 2002; Abe *et al.*, 2003) and flow stability (Shrivastava and Li, 2000; Li and Shrivastava, 2002). One group of current studies is focused on control algorithms both at the higher level, with desired acceleration being computed based on range, range-rate measurements and range policies employed, and at the lower level, with the throttle/brake being manipulated to follow the desired acceleration command accurately. Range policy is one of the factors which impact on string stability. The Constant Time-Headway (CTH) policy is commonly suggested as a safe practice for human drivers and is frequently used in ACC designs. Zhou and Peng (2005) studied impacts of CTH policy on string stability and concluded that for CTH policy, a sliding mode controller without using acceleration information can be designed to guarantee string stability.

Although string stability could be guaranteed in theory by a proper design of the ACC controller, effects such as response delays could affect string stability negatively. Many current results of ACC have shown that sensor-based ACC can significantly improve string stability. Vehicle-vehicle communication was one of the technologies recommended for ACC to ensure string stability (Sheikholeslam and Desoer, 1990). With sensor-based systems, sensor delay can take up to 100 ms, but with a vehicle-vehicle communication-based system, communication delay is normally at a level of 20 ms (Carbaugh *et al.*, 1998; Michael *et al.*, 1998). Bareket *et al.* (2003) studied the string stability impacts of sensor-based ACC using a combination of experiments, models and simulations. One of the main findings of the investigation is that string stability is not guaranteed with the current designs, but the degradation of performance, however, does not seem to be worse than that in the case of manually driven vehicles.

Yokota *et al.* (1998) performed detailed simulation to explore the effects of ACC on overcoming the bottlenecks caused by the decelerations of typical human driving, for example when encountering significant grade changes (–0.26% to +3%) on a highway. CTH was assumed for the ACC studied. Their study results show that even at the 20% penetration rate, the ACC vehicles significantly reduce the shockwaves; while at a higher level of penetration, the systems almost completely eliminate the shockwaves. Godbole *et al.* (1999) analysed the behaviour of two different autonomous ACC designs (with and without active braking) to determine their ability to respond to transient disturbance that occurs in highly congested freeway conditions. In their simulation, the first vehicle is driven manually, and it follows a speed trajectory recorded on highway I-880 in California by probe vehicles. The simulation results show that vehicle control under ACC is successful in following the preset headway while responding to various traffic disturbances. The average vehicle-following time gap for moderate traffic turns out to be 1.1 s when a set headway of 1.0 s is used. This translates into a highway capacity of 2770–2850 veh/l/h at a mean speed ranging from 25 to 30 m/s, supporting the hypothesis that a single-lane ACC system can result in higher throughput than today's highways. For stop-and-go traffic, a mean vehicle separation of 1.26 s at 9 m/s results in a traffic flow of approximately 2000 veh/h/l at a high rate of ACC utilization. Liang and Peng (2000) studied the ACC impacts on string stability. Their study results show that ACC can help improve the average velocity of the mixed traffic and reduce the average acceleration levels, resulting in high traffic flow rate, lower fuel consumption and pollutant emissions. Research by Bose and Ioannou (2001) shows that up to 60% of reduction in pollutant emissions can be achieved if 10% of the vehicles are equipped with ACC.

VanderWerf *et al.* (2002b) compared the effects of sensor-based ACC with vehicle-vehicle communication-based ACC by simulation. A 20 ms delay was assumed for communication-based ACC, compared to 200 ms for sensor-based ACC. The simulation result shows that with the sensor-based ACC, the disturbances are clearly damped out and shockwave propagation is significantly reduced further away from the disturbance vehicle; while with the communication-based ACC, both the precision and the closeness of the following vehicle are achieved and shockwaves are almost eliminated completely, and effects on increasing string stability are evident.

Safety Issues

One of the main positive impacts of ACC applications is that they can reduce occurrence of short time gaps (e.g. <1 s) where the following driver has to apply hard braking to avoid rear-end collisions. Many studies have been reported about ACC impacts on reducing rear-end collisions (Koziol *et al.*, 1999; Touran, 1999; Fancher *et al.*, 2001; Martin and Burgett, 2001). In ICC FOT studies, field operation test data were input to Monte Carlo simulation model, and it was estimated that ACC can reduce rear-end collisions by 17% (Koziol *et al.*, 1999).

One concern with ACC driving is that automation reduces mental workload of the driver to fulfil his/her driving task, and thus the driver becomes less involved in the vehicle control loop. In simulator experiments, Stanton *et al.* (1997) have observed reduced workload when driving with ACC from both mental and physical perspectives. As the systems aim to increase driving comfort, the brake capability of an ACC is limited (e.g. 0.3 g). The driver has to take over the control in situations where the preceding vehicle brakes in an emergency. For safe use of the ADAS functions, drivers need to know the limitations of the systems and also understand when and how the systems should be engaged and disengaged.

Another safety concern with ACC is drivers' slower response on a secondary task. According to ICC FOT results, driver response time to brake light stimulus of a leading vehicle and high level of leading vehicle deceleration, etc., were longer for ACC driving than manual driving, and sometimes drivers tended to wait for the system to respond before reacting (Koziol *et al.*, 1999). Such increased response time may pose a serious risk to the driver when encountering a safety critical situation, such as emergency braking or cut-in, where driver intervention is required.

Emergency braking is one of the dangerous situations for driving with ACC where the following driver has to intervene in order to avoid collision with the rapidly decelerating leading vehicle. This is the area where many current studies of forward collision warning and avoidance systems are focused. In a car following process, both the leading and the following vehicles travel in the same lane which makes it possible for the following vehicle to track the trajectory of the leading vehicle continuously. Because of continuous availability of range data of the leading vehicle, sensor-based systems have shown great potential to detect such emergency braking. Currently many results have been reported in this area (more details about collision warning systems are described in Section 'Collision Warning and Avoidance').

'Cut-in' is a another dangerous situation with ACC driving where initially a vehicle is following its preceding vehicle, then a vehicle travelling in an adjacent lane changes lane abruptly into the gap between the two vehicles. Because of limited braking capacity with ACC, the following vehicle becomes dangerously close to the cutting-in vehicle where driver intervention is required in order to avoid the collision with the cut-in vehicle. For sensor-based ACC, systems are more likely to be involved in cut-in scenario than manually driving due to conservative headway strategies applied (Aycin and Benekohal, 2000; Langheim *et al.*, 2002).

With sensor-based ACC, it is a challenging task to achieve early detection of a cut-in vehicle because of the limited angular and operation range of the sensors. Sometimes, a vehicle may drift to the lane border, but has no intention to change lane, and it often needs many filtered range data to determine a cut-in vehicle.

One of the solutions suggested to improve ACC safety in cut-in scenarios is by vehicle-vehicle communication where the cut-in vehicle transmits a clear message of lane changing (an equivalent of 'turning light') to the following vehicle at the instant it starts to make lane changing. The following vehicle would slow down and make space for the cut-in vehicle, making it possible to reduce the closing rate (i.e. differential velocity) to the cutting-in vehicle. The communication-based ACC vehicle would save a large amount of braking effort, which means more safety for the vehicle and less discomfort for the passenger (Xu and Sengupta, 2003).

Safety has been and will continue to be an issue with the application of cruise control assistants. More research is needed to further study the safety impacts of the application, particularly observation of ACC impacts in real traffic conditions to pinpoint the problems relating to human-machine interface and driver behaviour in using the system. Currently, few results have been reported about cut-in effects of vehicle-vehicle communication-based ACC. Obviously, this is one of the areas needing further study to explore the ACC impacts on safety, including comparison of safety effects between sensor- and communication-based ACC.

Collision Warning and Avoidance

The Challenges

Forward Collision Warning and Collision Avoidance (CW/CA) systems are mainly developed to reduce rear-end collisions, which represent about 28% of all collisions between vehicles (Vahidi and Eskandarian, 2003). Human drivers suffer from perception limitations on roadway emergency events, resulting in large delays in propagating emergency warnings due to line-of-sight limitation of brake light and large processing delay (driver reaction time). Collision warning and avoidance systems can react to situations that human drivers cannot or do not, due to driver errors. The National Highway Traffic Safety Administration (NHTSA) estimates that about 88% of rear-end collisions in the USA are caused by driver inattention or too close following (Zador *et al.*, 2000). The fact that such a large percentage of rear-end collisions are due to driver inattention or misjudgement, the emerging technology for forward looking detection (e.g. millimetre-wave radar) suggests a large potential gain from successful implementation.

Forward collision warning systems are designed to provide warnings (visual, audible or haptic mode) to a driver when an imminent crash with the leading vehicle is detected (Krishnan *et al.*, 2001). Collision avoidance systems will take action if a driver fails to respond to the warning given, depending on the system, for example by applying a limited brake to reduce the speed of the impact or full brake to avoid the collision. Traditionally, the CW/CA concepts have emphasized driver alerting and warning rather than automatic vehicle control. However, the successful demonstration of various vehicle control technologies, for instance, ACC, suggests that the safety performance of CW/CA system could be further improved by active braking (Vahidi *et al.*, 2003).

Determining the minimum safe following distance is one of the key tasks for any collision warning and avoidance system. This is a threshold on the basis of which it makes decisions and actions for providing warning and/or active braking, ensuring that no inter-vehicle collisions will occur when the preceding vehicle brakes in an emergency. It is a very challenging task to determine such a value in the car following process, as many factors can have impacts on it including:

- current speed of both the proceeding and the following vehicles;
- braking capabilities of both the proceeding and the following vehicles;
- loading conditions of both the proceeding and the following vehicles;
- road geometry condition;
- road surface condition which relates to tyre-road friction; and
- reaction time.

It is challenging to get all the information fed into the control algorithms around the clock and in all weather conditions. Most of the current systems have fixed gain controllers (i.e. control algorithms with linear relationship between input and output variables) (Yanakiev *et al.*, 1998; Vahidi *et al.*, 2003). However, vehicle parameters vary during the lifetime of the vehicle. Certain vehicle or road parameters, for example tyre-road frictions, could change during the single trip. The issue of sensitivity to parameter variations is especially important for heavy vehicles. Currently, various CW/CA technologies are under research and development including on-board sensors and vehicle-vehicle communications.

Autonomous Systems

Current CW/CA systems under research and development are predominantly autonomous. In such systems, the key technology used is ranging sensors, for example millimetre-wave radars or infrared lasers (similar to those used for ACC), which are used to detect and track the preceding vehicle. With this approach, inter-vehicle distance, speed and relative speed are directly measured or derived from the sensor adopted. Both the warning and the braking critical distances are defined as the functions of vehicle velocity and relative velocity (Seiler *et al.*, 1998; Maltz and Shinar, 2004).

Significant achievements have been made in the development of autonomous systems, and some sensor-based systems have already been applied for commercial vehicles, for example, Eaton's VORAD using millimetre-wave radars to scan the road within a 12 degree arc in front of the vehicle. Although some Jaguar models feature a 'Forward Alert' function which uses the forward looking radar to warn of possible collisions even before ACC was introduced on the market, applications of collision warning systems are still at a limited level of passenger car market.

One of the concerns with current systems is with regard to nuisance alerts. These are troublesome because the systems need to be able to detect stationary obstacles (such as a parked vehicle) in an environment complicated by many clutter sources, such as bridges, signs, guardrails and other features of the roadway infrastructure. The current technology is not good enough to readily distinguish these kinds of clutter from the stopped vehicles that the systems must detect, so the systems tend to issue alerts even in the absence of real hazards. Since real hazards are relatively infrequent, this raises the likelihood that drivers will ignore the alerts for those hazards or will deactivate the systems entirely (Vahidi *et al.*, 2003).

In the USA, a field operational test project of Automotive Collision Avoidance System Field Operational Test (ACAS FOT) was run from 1999 to 2004 to further the understanding of sensor-based FCW systems by conducting an extensive FOT with drivers. In the test, 13 Buick LeSabre (2002 model year) vehicles were driven by 96 test subjects as their own personal cars for three or four weeks. One of the key results highlighted was the issue of false alarms. When the FOT began in March 2003, the initial acceptance response of the ACAS system was much less positive than was reported by participants during earlier pilot testing. This dissatisfaction was based on what drivers considered being 'nuisance alerts' (or false alarms). About half of the alerts were due to stationary objects along the roadside being detected by the radar and erroneously classified as 'threats' to the host vehicle. Many other alerts occurred under conditions that drivers felt did not warrant an alert. The test results clearly suggest that further reductions in false alarms (resulting in a higher proportion of 'credible' FCW alerts) are needed to ensure widespread FCW system acceptance (Ervin *et al.*, 2005).

Although forward ranging sensors provide a practical solution to reduce rear-end collisions, the prices of the traditional systems available today (typically based on radar sensors) and their limited performance (narrow field of view and poor lateral resolution) have prevented such systems from entering the market on a large scale. Currently, many efforts are being made to improve the performance of autonomous systems, for example, using multi-sensors (Zhang *et al.*, 2005) to detect not only moving vehicles but also stationary vehicles and combine other technologies such as vision (Srinivasa *et al.*, 2003) to reduce false alarms. Fusion of radar and vision is another approach of interest to many people, where the radar gives accurate range and range-rate measurements while vision solves the angular accuracy problem of radar. One of the suggestions to improve the accuracy of the critical distance calculated is to include coefficient estimation of tyre-road friction into the control algorithms, for example, by using results from shaft angular velocity sensors or road sensors (Seiler *et al.*, 1998; Barton *et al.*, 2002).

The main advantages of autonomous systems are that each driver has his/her own systems on board and the technology/function is easy for the driver to understand. In addition, system operation does not rely on other parties (e.g. vehicles or road infrastructures) and, therefore, can be implemented on current road infrastructures. However, with such an approach, some of the key information required for calculating braking distance is not available, for example braking capacity of the preceding vehicle. Currently, no systems are available on the market which are able to avoid collisions in extreme scenarios, i.e. emergency braking, although significant achievements have been made in the research of control algorithms and technologies. Apart from the requirements of more complicated control technologies (hardware and software), liability is one of the key issues to be resolved for such systems, because the actions taken by the system may be against the driver's will. To make an avoidance system which is acceptable to users and manufacturers, the operation of the systems should affect normal driving as little as possible and in the mean time be able to avoid collisions.

Cooperative Systems

Vehicle-vehicle communication is one of the main technologies being tested for the development of cooperative collision warning and avoidance systems. Unlike the autonomous systems where the braking capacity of the preceding vehicle is based on estimation or assumption, vehicle-vehicle communication makes it possible for the preceding vehicle to transmit the information to the following vehicle, for example braking capacity or even loading status.

Misener and Sengupta (2005) examined and demonstrated wireless-enabled vehicle-vehicle cooperative safety systems for collision warning including FCW assistant, intersection collision warning and lane change warning. The performance of the systems was demonstrated at two sites: the PATH Richmond Field Stations (RFS) and Crows Landing with five 1997 Buick LeSabres being involved in the demonstration. The demonstration proved the concept that inter-vehicle communication to support collision warning and avoidance functions effectively.

With an autonomous approach, multi-sensors are required to detect threats coming from different directions and ranges of the vehicle. The system would become very complicated and expensive to implement. Vehicle-vehicle communication makes it possible to 'detect' threats from any direction and range for applications such as forward collision warning, intersection collision warning, lane change collision warning (Ioannou and Stefanovic, 2005; Jin and Recker, 2006). Moreover, a radio is significantly cheaper than the suite of sensors required for giving 360 degree awareness. Therefore, it might be a cheap and simple solution to support the collision warning and avoidance systems in the future.

With on-board sensors, a judgement of emergency deceleration of the preceding vehicle is based on filtering of the detected speed profile, thus response delay can take up to 0.3 s. With a vehicle-vehicle communication-based system, a clear message of emergency braking can be transmitted from the leading vehicle to its following vehicles, thus response delays can be reduced to a level of 0.1 s (Choi and Hedrick, 1995; Gerdes and Hedrick, 1995; Carbaugh *et al.*, 1998; Michael *et al.*, 1998).

With an autonomous approach, the system can only respond to the vehicle immediately in front. While with vehicle-vehicle communication, the emergency braking information can be sent to all the following vehicles simultaneously; this significantly reduces the delays for preventing multi-vehicle vehicle collision (Yamada, 2002). This is particularly important in situations of high-volume traffic where vehicles follow each other closely.

In situations where a vehicle is equipped with road surface sensors, it can transmit the road surface information to its following vehicles via vehicle-vehicle communication. With such information being integrated into the control algorithms, it is possible to calculate the safe following distance more accurately. Information on such road surface condition can also be provided to the vehicle from road infrastructures if road-vehicle communication is available (Tsugawa, 2005).

Although significant achievements are being made, currently no cooperative collision and avoidance systems are ready for market introduction. There are many issues to be resolved including both technical issues, for example, developing robust wireless vehicle-vehicle communication systems, and legal issues especially for collision avoidance systems, for example liabilities of different parties involved if an accident occurs with the system.

Legal Issues

General legal issues regarding ADAS have been addressed in several studies (e.g. Becker, 1996; Feldges and Brandenburg, 2000; Stevens and Strang, 2001; van Wees and Brookhuis, 2005). Feldges and Brandenburg (2000) examined the legal framework for testing and market introduction of ADAS systems, where different ADAS functions were analysed under the legal systems of France, Germany, Italy, Spain, Sweden and the UK. In the study, the legal implications of ADAS systems were studied covering rules of traffic law, criminal law, civil liability of drivers, owners of vehicles, car manufacturers and the suppliers. The analysis highlights that legal impacts of ADAS systems are greatly dependent on the level of the support realized. Information or warning systems, intervention systems with and without possibility of overriding should be distinguished. Since a driver's liability is based upon fault, he/she will not be liable for damage caused by systems he/she could not override. In RESPONSE 3 (a subproject of PReVENT project), a code of practice for the design and evaluation of ADAS has been developed where the concept of controllability and procedures to prove controllability of ADAS systems are clearly defined (RESPONSE 3 Deliverable, 2006).

In the case of warning systems, the driver will be alerted to take the appropriate action to respond to the potential dangers (e.g. by optical, acoustic or haptic means), and there would be no direct intervention from the systems to the main driving activities (steering, accelerating, braking, steering). Because information/warning systems do not change driver roles in controlling vehicles, there is less chance that manufacturers are liable in accident scenarios (Feldges and Brandenburg, 2000). Currently, some information/warning systems have already been deployed under current legislation in Europe, America and elsewhere in the world; examples include forward collision warning and lane departure warning systems, etc.

The situation becomes complicated for systems with intervention capabilities. Compared to information/warning systems, the system automates some of the vehicle control tasks and becomes more effective in achieving optimized vehicle control. In this situation, the driver becomes less involved in direct control of the vehicle and the legal liability may shift from drivers to manufacturers. ACC is a good example of such systems. The system provides automatic headway control when following another vehicle, but the driver can override the ACC function whenever needed or wanted. Such systems would not change the responsibility of the parties as the ultimate control of the vehicle remains with the driver (FHWA, 1998). For such systems, it is crucial for the users to be aware of system functions, limitations and the conditions for using the system. However, manufacturers should not simply restrict their liability for products that do not meet an acceptable level of safety by arbitrarily defining only one specific use as 'normal' or by the mere statement that, because systems can be overruled by the driver, responsibility remains (entirely) with the driver (van Wees, 2000; van Wees and Brookhuis, 2005). It is their primary duty to market a safe product. This might, for instance, imply a duty to design a system in such a way that it cannot be used in a hazardous manner or under hazardous circumstances (for instance speed ranges or type of roads the system was not designed for).

For intervention systems which do not allow a driver to override the function, system manufacturers are more likely to be liable for any accidents (Feldges and Brandenburg, 2000). The systems can be divided into two groups: systems in which the intervention cannot be overridden, as a result of their construction (e.g. mandatory ISA systems which do not allow driving beyond the speed limit in any cases), and systems where the intervention cannot be overridden because the time left for the driver to react is too short (e.g. collision avoidance systems with active brake control at a safety critical situation). With collision avoidance systems, they can potentially overturn a driver's decision, which results in some unforeseen situations. System failures in such applications may result in catastrophic consequences with multi-vehicles, and primary and secondary collisions being involved. Therefore, it is important to have laws to address the legal liabilities of different parties involved including drivers, car manufacturers, suppliers and road owners. For such systems, liability issues are stronger challenges than technical barriers (Vahidi *et al.*, 2003).

In a study by van Wees *et al.* (2005), the European Product Liability Directive's concept of a defective product is analysed from both a legal and a human factors perspective. In answering the question of how to determine the 'defectiveness' of ADAS systems, i.e. what standard to apply to judge a product as defective, two different approaches are suggested: consumer expectations and risk-benefit analysis. With the first approach, a product is defective when it does not provide the safety a person is entitled to expect. The problem with the application of a consumer expectation test in the context of complex and innovative products such as ADAS is that users may generally have no idea how safely a product ought to perform in all foreseeable situations, or how safe it should be made against all foreseeable hazards (Miller and Goldberg, 2004; van Wees and Brookhuis, 2005). Furthermore, due to lack of experience, expectations of consumers have not yet been sufficiently established to define an expected standard of performance. Although a risk-benefit approach might help to solve some of the problems in applying a consumer expectation test, it is not without difficulties. A first major difficulty associated with a risk-benefit approach is the complexity of assessing risks and benefits since balancing factors should be somehow comparable and quantified in comparable values, preferably in monetary terms. However, design decisions often involve trade-offs between factors of a very different nature (e.g. safety vs. comfort). Furthermore, figures on the cost-effectiveness of an alternative design or presentation of an alleged defective product are at best crude estimates and generally not available to courts, therefore, making judgement of courts to a large extent an intuitive one (van Wees and Brookhuis, 2005).

van der Heijden and van Wees (2001) undertook a study to understand whether or not present legislation frameworks are able to accommodate a smooth development and market implementation of ADAS, which is strongly related to the aspect of traffic safety. Various aspects related to liability issue were analysed based on an exploration of the functionality and possible failure of ADAS. In particular, attention was paid to the need for establishing safety requirements to the design and marketing of ADAS as well as the issue of liability regulation. The study concluded that current legal frameworks in both the fields of vehicle safety standards and liability provide some flexibility towards technical developments regarding ADAS, i.e. these frameworks do not contain many 'hard rules' obstructing the introduction of ADAS. Concerning the safety regulation of ADAS, it is argued that the speed of technological developments and the innovative and specific nature of ADAS technology generate various tensions. Public authorities are recommended to invest more in building a shared and public knowledge base regarding ADAS.

Compared to autonomous ADAS, more parties (e.g. road operators, traffic operators and communication network providers) will be involved in the development and operation of cooperative systems. This will increase liability complexities of cooperative systems. If an accident occurs with the ADAS, it would be a challenging task to know which partners should take the responsibility. It could be caused by defects of mechanic or electronic parts of the systems, wrong information from the infrastructure side, or failure with the communication network. In order to clarify the liabilities in an accident, one of the solutions suggested is to make the vehicle equipped with a data recorder to help determine the true causes of the accident involved. However, it should be noticed that the availability of stored data on system performance and driving behaviour raises additional legal issues such as the question whether these data can be used for other purposes such as criminal charges against the driver (van der Heijden and van Wees, 2001).

ADAS Implementation

ADAS implementation is a complex issue that involves a wide range of technologies, user acceptance and government policies. The issue has been discussed in several studies including Marchau and van der Heijden (2000), Marchau and Walker (2003), van der Heijden and Marchau (2005) and Lu *et al.* (2005). In the study by Marchau and Walker (2003), an integrated approach was proposed with respect to ADAS implementation. They concluded that large uncertainties exist including external development, the outcome of ADAS policy decisions and the valuation of the outcomes by stakeholders involved in or affected by ADAS policy decisions. To deal with such uncertainties, an adaptive approach was proposed which includes both current and future actions to allow adaptations over time as knowledge about ADAS accumulates and critical events for ADAS implementations take place.

Several issues regarding ADAS implementation were identified by van der Heijden and Marchau (2005), including limitations of in-vehicle technologies, technology reliability and gaps between market preferences and government goals. Three levels of decisions were proposed for understanding the complexity of ADAS implementation: (1) strategic or long-term decisions about development and marketing of ADAS systems; (2) tactical or medium decisions about ADAS use strategy of drivers and transport service providers; and (3) operational or short-term decisions about the direct use of the driver support systems by drivers. They concluded that people should not make simple, straightforward assumptions on how ADAS will influence driver behaviour, the interaction between traffic participants and the performance of the transport systems as a whole. Many mechanisms and effects are still uncertain due to lack of adequate behaviour theories and empirical evidence.

Regarding longitudinal control ADAS systems discussed in this article, the following are identified as important for large-scale implementations:

Integrated Approach to Develop ADAS Systems

In-vehicle technologies are dominant with current ADAS system development. Although in-vehicle technologies such as on-board sensors are effective to detect the existence and movements of the preceding vehicle, they have the limitation that they cannot work beyond the operative range of the sensors. For example, braking capacity and loading status of the preceding vehicle are very important for calculation of minimum safe stopping distance from the vehicle in front. Such information is difficult to be collected through detection. Another example is driving with ACC where cut-in is one of the safety risks identified. With on-board sensor-based systems, it is difficult to make an early detection of a cut-in vehicle until the vehicle crosses the lane marking. However, with cooperative ACC, lane changing intention of the preceding vehicle can be 'detected' via vehicle-vehicle communication.

Automotive industries are making huge investment in the development of ADAS systems in order to increase compatibilities of their products. The gap between in-vehicle intelligence and roadway intelligence is getting larger. For highway authorities, any modifications of road infrastructure at a network level will involve a large amount of investment from government, and the policymaking of public authorities is often regarded as a long and inefficient process. With cooperative systems, especially systems based on road-vehicle communications, it will inevitably face the 'chicken-and-egg' problem in their implementation. One of the issues is whether the road infrastructure or vehicle intelligence should come first. Tsugawa (2005) suggested future ADAS systems should be developed to serve multi-purposes such as safety, information and convenience to increase motivations for infrastructure sides to get involved in the development of ADAS systems.

Accuracy and Reliability

Accuracy and reliability of ADAS is a key issue for ensuring safety of both equipped and non-equipped vehicles. For ADAS systems to get user and government acceptance, they must prove that they are able to work safely in all weather conditions around the clock. Most current ADAS systems are built on the basis of on-board sensors. For some ADAS functions, further efforts are needed to increase accuracy and reliability of the technology (both hardware and software) in order to achieve large-scale applications. Taking FCW systems as an example, although the system has been introduced to the market for nearly ten years, most of them are limited to commercial transport vehicles due to frequent false alarms with the system. Unlike professional drivers who can be trained to deal with the false alarms, it is regarded as risky to introduce such systems to general drivers. Another concern with current in-vehicle technologies is that some on-board sensors are too sensitive to weather conditions, for example, performance of laser ranging sensors degrades significantly in fog and wet weather conditions. Currently, many efforts are being made by manufacturers to improve performance of on-board sensors, including (1) improved sensor performance by using more sophisticated technologies; (2) data fusion of different types of sensor results; and (3) redundant sensors. Currently, high cost and unreliable performances (hardware and software) are still the key issues for large-scale implementation of many ADAS systems.

Driver Behaviour Studies for Impact Assessment

Sound impact assessment is very important for convincing decision-makers of large-scale implementation of ADAS systems. As ADAS penetration levels have not reached the level at which ADAS impact can be observed directly to validate the behaviour modes, most of the current impact assessments are based on traffic simulation (microscopic and macroscopic). This requires sound knowledge about driver behaviour in both baseline and ADAS scenarios.

Regarding driver models in baseline conditions, understanding driver behaviour under different traffic conditions is still one of the major challenges. Unlike driving with ADAS support, manual driving varies according to the traffic conditions encountered. In this area, further studies are needed to understand driver's natural behaviour, especially braking and acceleration behaviour in congested traffic conditions (e.g. 'stop and go'). For driving with ADAS, one of the key areas is to get empirical evidence to understand how drivers use the systems (e.g. engage and disengage with ACC), and interactions between equipped and non-equipped vehicles. This means further microscopic studies of driver behaviour, for example by field trials using instrumented vehicles.

Final Remarks

The major advantages of autonomous systems are that drivers have their own sensors to detect preceding vehicles and the system operation does not rely on other parties; therefore, the systems can be applied under current road infrastructures. However, sensor-based systems will only regard threats within the immediate vicinity of the equipped vehicle and cannot go beyond the operative range of the sensors. The main advantages of cooperative systems are that the information and data which are difficult or impossible to measure directly through in-vehicle technologies can be collected through vehicle-vehicle or vehicle-infrastructure communication; therefore they have a great potential to further improve traffic safety and efficiency. Unlike autonomous systems which are mainly driven by car manufacturers, cooperative systems make it possible for wide and balanced interests, such as safety and traffic operation, to be considered in the development and implementation of the systems.

Most current results of ADAS impact assessment are based on traffic simulation for which driver behaviour models are crucially important. With the increased penetration levels of ADAS systems (e.g. ACC), it has become possible to get more empirical evidence of driver behaviour in real traffic conditions. On the one hand, such field data can be used to understand how drivers use the system, interactions between equipped and non-equipped vehicles and driver behaviour adaptations. On the other hand, new evidence of driver behaviour can be input to traffic simulation model for improving impact assessments.

Understanding how ADAS systems may impact on the environment is of interest to many transport researchers, as road traffic is one of the major contributory factors to air pollution. For ADAS systems, particularly those supporting longitudinal control such as ACC and Stop&Go, they are able to respond to speed and spacing changes of the leading vehicle more quickly and more accurately than manual driving, which results in more stable and smooth traffic and reduces fuel consumption and pollution. Compared to studies on safety and efficiency impacts, few are reported on ADAS impacts on environment (e.g. fuel consumption and pollutant emissions). This is one of the areas where further studies are needed.

Providing road surface information and topology data is very important for improving ADAS functions, particularly for collision warning and avoidance systems. Such information can be obtained by using on-board sensors or by infrastructure-vehicle communication where road operators provide relevant data to ADAS-equipped vehicles. Many issues exist for engaging road operators to support ADAS functions including clarification of roles and responsibility of car industry and road operators, business case of road operators, and funding mechanisms for infrastructure investment.

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