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Published in:
Transportation Planning and Technology

DOI:
10.1080/03081060500120282

2005

Link to publication

Citation for published version (APA):
Lu, M., Wevers, K., & Heijden, R. V. D. (2005). Technical feasibility of advanced driver assistance systems (ADAS) for road traffic safety. *Transportation Planning and Technology*, *28*(3), 167-187. https://doi.org/10.1080/03081060500120282

Total number of authors:
3

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Transportation Planning and Technology, vol 28 issue 3 pp 167-187.
http://dx.doi.org/10.1080/03081060500120282

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Technical feasibility of Advanced Driver Assistance Systems (ADAS) for road traffic safety

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ABSTRACT: This paper explores the technical feasibility of five Advanced Driver Assistance System (ADAS) functions to contribute to road traffic safety, to reach stated European (EU) and national road traffic safety targets. These functions - enhanced navigation, speed assistance, collision avoidance, intersection support and lane keeping - were selected from previous research as adequate substitutes for infrastructure related measures. State-of-the-art enabling technologies (like positioning, radar, laser, vision and communication) and their potential are analysed from a technical perspective, and possible obstacles for large-scale dedicated ADAS implementation for road traffic safety are discussed.

KEYWORDS: ADAS; autonomous systems; communication; co-operative systems; road traffic safety; sensor technologies

INTRODUCTION

Road traffic accidents are perceived as one of the major societal problems in the world today. According to an estimate by the World Health Organization, 1.2 million people are killed and as many as 50 million injured in road accidents every year. Projections indicate that these figures will rise by about 65% over the next 20 years unless there is increased commitment to prevention [1].

Traffic is the result of interaction between people, vehicles and road infrastructure. In this process the human is a key element, but also the weakest link. Nearly all traffic accidents are due to human error. Measures to counteract traffic accidents can be categorized into one of three approaches: (1) change human behaviour; (2) vehicle-related measures; and (3) physical road infrastructure related measures. Another categorisation is based on passive safety measures that aim to mitigate the consequences of an accident once it has happened, and active safety measures that aim to avoid accidents. Each of the first three categories contains both passive and active elements. Changing behaviour is promoted by enforcement, information, education and driving instruction, and is largely in the domain of active safety. Related measures are dependent on government initiated action, and their effects are often not lasting.

For vehicle-related safety measures in particular, a distinction is made between passive components (like car body structures, head restraints, seatbelts and airbags) and active components (like tyre quality, electronic stability control [ESC], anti-lock braking [ABS] and so-

called Advanced Driver Assistance Systems [ADAS]). Systems like ESC and ABS help to avoid accidents in critical situations, while ICT (Information and Communication Technology) based ADAS applications help to avoid accidents by assisting the driver in their driving task continuously, but in addition have the function to increase comfort and efficiency. Table 1 provides an overview of safety related ADAS applications.

Table 1. Overview of safety related ADAS applications

ADAS function	Definition and/or description	Level	Impact
navigation system	provision of vehicle positioning, route calculation and route guidance	I+S	long
adaptive cruise control (ACC)	automatic control of speed and distance in relation to the proceeding vehicle in the same lane	C	long
adaptive light control (ALC)	dynamic aiming headlamps and situation adaptive lighting	S	long
vision enhancement	assist driver vision capability in adverse lighting and weather conditions by providing enhanced visual information	S	long
legal speed limit assistance	assist driver in keeping within (static or dynamic) legal speed limits	I/W/C	long
curve speed assistance	assist driver in keeping within an appropriate and safe speed in curve manoeuvres	W/C	long
dangerous spots warning	assist driver by providing information or warning on a dangerous location (based on accident statistics) at inappropriate speed	I/W	long
stop and go (S&G)	assist driver by taking over full vehicle control in congested stop-and-go traffic at low speeds (automated lane keeping and platooning)	C	long
forward collision avoidance (FCA)	warn driver in case of an imminent forward collision, and/or provide automatic control of the vehicle in such situations	W/C	long
lane keeping assistant (LKA) (= lane departure avoidance)	assist driver to stay in lane (on unintentional lane departure or road departure) by warning (e.g. by rumble strip sound) and/or semi-control of the vehicle (by force feedback on the steering wheel) and/or full control	W/C	lat
lane change assistant (LCA) (= lateral collision avoidance)	for change-of-lane manoeuvres, provide information about vehicles in adjacent lanes, and/or warning for potential collision, and/or vehicle control in case of imminent collision	I/W/C	lat
intersection collision avoidance (ICA)	avoid collisions at intersections by warning or control based on: -radar and/or vision -vehicle positioning and short-range communication (requires all participating vehicles to be equipped)	W/C	long
intersection negotiation	regulate vehicle traffic at intersections based on vehicle positioning and short-range communication in all participating vehicles	C	long
autonomous driving	fully automated driving in controlled motorway situations at all speeds by full lateral and longitudinal control	C	lat+long

Source: Partly based on NextMAP Consortium [32].
Level: I = information, W = warning, C = control, S = support
Impact: long = longitudinal, lat = lateral

Physical road infrastructure related measures focus largely on active safety, but also have passive elements: the infrastructure could be constructed such that accidents are less likely to happen, and that the consequences are less serious once they do happen. Related concepts are 'self-explaining roads' [2], that have a recognisable road layout dependent on the road category, and thereby induce adequate behaviour, and 'forgiving roads', that have structural layout elements that reduce the consequences of accidents once they happen. The Swedish infrastructure approach states that the layout of infrastructure should inform the driver in a natural and implicit way about intended use and expected behaviour, and help to prevent encounters at high differences in speed and direction, by implementing the following basic guidelines, with separation of different types of traffic as an important principle:

- never mix vehicles with other slower forms of traffic at speeds higher than 30 km/h;
- never have level road junctions with speeds higher than 50 km/h; and
- never have oncoming traffic without separation at speeds higher than 70 km/h.

Since the early 1990s, especially in several European countries, large-scale programmes for infrastructure redesign have been elaborated. However, their full implementation covers several decades and requires considerable investment [3]. In the meantime the development of ADAS is progressing further, and several applications come closer to possible high volume introduction.

This paper focuses on five safety related ADAS functions - navigation, speed assistance, collision avoidance, intersection support and lane keeping - which were identified in previous research as potential substitutes for infrastructure related measures [3]. In the following sections the technical feasibility of these ADAS applications is analysed in terms of the state-of-the-art of their core technologies (positioning, radar, laser, vision and communication), and as both autonomous and cooperative systems.

NAVIGATION SYSTEM

The navigation system is a state-of-the-art system, which comes in many different variants, and with user interfaces of different levels of sophistication. It rapidly gains popularity, even for the average driver, as it provides not only route guidance but also dynamic traffic information, best route alternative, and estimated time of arrival. Vehicle positioning (i.e. inertial sensors, GPS and map matching), route calculation (i.e. map database) and route guidance are the main system components. Several of the physical infrastructure design requirements to enhance road traffic safety could also be addressed by the navigation system with minimal adaptations including: (1) minimising the part of journey on relatively unsafe roads; (2) making journeys as short as possible; (3) letting shortest and safest routes coincide; (4) avoiding search behaviour; and (5) making road categories recognisable [3].

By its very nature, a navigation system implements the fourth requirement. Requirements (1), (2) and (3) are fairly closely related, and in a sense already implemented in a navigation system, to the extent that the outcome is still dependent on the route selection choice that the user has made. The available options for this choice generally include: fastest route; shortest distance; main roads (as much as possible); and avoid main roads (as much as possible). A navigation system in principle creates the shortest (or fastest) route (i.e. requirement (2)) in balance with the chosen route selection criterion. The higher the level of the road, in general the better the separation of different kinds of traffic will be, and therefore the safer the route (requirements (1) and (3)). The main roads option therefore likely provides the best balance between requirements (1), (2) and (3). The result is dependent on the choices that the map data-

base provider has made with respect to the categorization of roads, and on the route calculation choices that are made by the software in the navigation system. As an example, setting the shortest route does not always provide the real shortest route, but a smart shortest route, still taking into account some principle of preference of higher level roads and avoidance of residential areas. In view of improving safety, some harmonization of road categorization in the map database and of route selection criteria for navigation systems might be considered. Input from public authorities for this is desired.

Requirement (5) is very much related to the concept of 'self-explaining roads'. Of course, a navigation system could in principle inform a driver about the type of road being driven, to induce appropriate driving behaviour, and in particular the right speed. However, a speed assistance system would in a much better and less intrusive way inform the driver of the expected driving behaviour.

It should be noted that the navigation system also provides a platform for the provision of road traffic information, currently mainly provided as TMC (Traffic Message Channel) messages over RDS (Radio Data System), a data channel in the FM sideband. An example of safety related traffic information is the provision of the precise location of the tail of a traffic queue, which could be based on the recently developed TMC Forum Specification for Precise Location Referencing [4].

Several ADAS applications could benefit from map and position data (the map database and vehicle positioning as additional sensor). Examples are curve warning (to provide curvature information for an oncoming curve) and adaptive cruise control (to detect that a tracked vehicle is temporarily lost due to an oncoming curve). A key concept is the ADAS horizon, which provides an extract of the map database ahead of the vehicle. In the ADASIS Forum and the EU funded MAPS&ADAS project, an ADAS Interface Specification is developed [5] to define the related concepts and to standardise the data streams. An ADAS Horizon Provider (AHP) extracts map data and vehicle position, and provides these data continuously via the vehicle bus system to various applications. On the ADAS application side, an ADAS Horizon Reconstructor takes the required information from the data stream and prepares these for the application. The AHP can be incorporated in the navigation system, that already includes map data and vehicle positioning, but alternatively the map data and vehicle positioning could be made a separate unit (the so-called map server), that serves both the navigation system and the AHP.

SPEED ASSISTANCE

Inappropriate or excessive speed is a crucial risk factor in traffic accidents [1], especially in the urban environment and on single carriageway urban roads. Therefore one of the key practical and operational control parameters of active safety is speed. ADAS provides technologies to address the issue of speeding, and to promote better (or even complete) conformance with speed limits than other measures like police enforcement, education and improved layout of physical infrastructure.

Although infrastructure based speed assistance is possible, it is generally accepted that future systems will be map-based. In an infrastructure based system the (rough) position of the car and the information regarding the speed limit may be obtained from short-range communication beacons or transponder tags, which may be installed at speed limit changes (in general at speed signs along the road). High infrastructure installation and maintenance costs seem to

be prohibitive, while on the other hand the increase of ADAS components in the car favours the in-vehicle integration of a map-based system.

Map-based speed assistance uses vehicle positioning, determination of the local speed limit (from map database information), comparison of the actual vehicle speed with the local speed limit, and information or warning, or vehicle control. Vehicle positioning and a digital map database are likely to be common components in every car in the future, and are already standard components of the navigation system. Comparison with the actual vehicle speed is standard technology, as is information or warning through an HMI (Human Machine Interface), or vehicle control (overrideable or non-overrideable).

System Design Options

Speed assistance systems may be designed in several different ways. An important element is the feedback model that is chosen, for which in general four different levels are distinguished: information (visual or acoustic), warning (acoustic or haptic), overrideable control (haptic throttle) or full control (fuel supply control, gear change and/or braking). Another determinant is the mode of operation, which can be voluntary (on/off switch) or mandatory (autonomous, as soon as the engine is switched on) [6]. In recent years many pilot schemes have been carried out in different countries (e.g. Sweden, UK, France, The Netherlands and Australia) [7 /11], in which various system set-ups have been tested and demonstrated, and also user response and acceptance have been investigated. In these projects the technical feasibility of different speed assistance approaches has been amply demonstrated. Lu et al., [3] has suggested introducing a sophisticated flexible system layout that differentiates according to road type and traffic safety requirements, including:

- mandatory full control on roads and crossings with mixed traffic;
- mandatory overrideable control (haptic throttle) on single carriageway roads with separation of traffic categories; and
- voluntary warning on dual carriageway roads specifically designed for motor vehicles.

The rationale for this differentiation is based on accident data, the focus of proposed infrastructure measures for traffic safety, and driver acceptance. Motorways are considered to be relatively safe, and do not feature so much in infrastructure redesign programmes as they already largely comply with proposed standards. Most accidents happen in urban areas and on single carriageway through roads. Infrastructure measures have a strong focus on speed control in these areas. Conversely, limitation of the freedom of the driver to be in full control of their car is likely to be most strongly felt in the motorway environment.

Prerequisites for Speed Assistance

A speed assistance system needs reliable determination of the vehicle position in the map, and up-to-date speed limit information in the map database. Vehicle positioning as implemented in current navigation systems is very accurate. Only occasionally an error may occur, and for a very short period of time. In such cases the positioning unit generally knows the uncertainty in the vehicle position, and a warning to the driver may be issued by the speed assistance system that reliable speed limit information is not available. The future introduction of the European Galileo satellite positioning system, which will include integrity information, and local augmentation systems to fill local gaps in satellite reception, may further improve future positioning capabilities.

The issue of the availability and reliability of speed limits in digital maps has been addressed by the eSafety Working Group on Road Safety [12]. It is argued that market forces currently push for extension of trip and travel related content of digital map databases, and not so much for inclusion of safety relevant road network data such as speed limits. The conclusion is that due to commercial constraints a European road safety (ADAS) map database is not likely to appear on the market as a sufficiently low-cost product, which would enable large-scale take-up of safety applications.

It is questionable if this view is correct. Inclusion of new content in commercial map databases is indeed dependent on market forces. If car manufacturers would in the coming years increasingly offer safety related ADAS applications as an option in their car models, this might be a driving force for such inclusion. But, if the public is not willing to pay more for such options, analogous to the experiences with traffic information services [12] and emergency call applications, then car makers may be reluctant to offer such applications. However, market forces might be steered significantly if speed assistance could be implemented gradually as a mandatory system, as indicated above, according to a European roll-out plan, in new as well as in existing cars. A further conclusion [12] is that a European road map database containing additional agreed attributes for driver support and advisory purposes should be produced, maintained and certified under the responsibility of a public-private partnership and made available at acceptable prices for end users (possibly free of charge).

To enable up-to-date speed limits in digital map databases for in-vehicle applications, two prerequisites need to be fulfilled. First, the responsible authorities need to organize the legal speed limit information for their roads in a timely and accessible way and provide this information and especially changes thereof to digital map database suppliers on a continuous basis. This would enable the provision of certified speed limit data (as proposed in [12]). However, an enormous effort is needed here. In general different authorities within a country are responsible for different parts of the road network. Current systems for recording traffic regulations, including speed signs, come in many different variants, are often inaccessible and sometimes even nonexistent. A harmonized implementation of solutions to this problem would need to be organized at a European level, including solutions for storage and maintenance of road attribute data by authorities and standardization of exchange mechanisms. Some of the issues involved are being studied in the French-German funded SafeMAP project and in the EU funded projects SpeedAlert and MAPS&ADAS [5,13,14].

Second, incremental map data updates with respect to speed limits need to be supplied to the vehicle in a timely manner, and integrated into the map database in the vehicle. This needs a method for incremental updating, as has been explored in the EU funded ActMAP project [15], and a suitable data versioning and transfer mechanism to get the right updates in every vehicle.

Introduction of speed assistance by statutory regulation (including the aforementioned differentiation) as an enforcement mechanism, while maintaining the legal liability to obey the posted speed traffic signs, may adequately address the liability issue, and allow speed assistance to be already used if speed limit data in digital maps is not yet complete and up-to-date.

Further Perspectives

Going one step beyond what is generally discussed, speed assistance could also be used to regulate speed at the approach of intersections, including a slow-down to an adequate speed,

and a full stop at a stop sign or a red traffic light. In the latter case the traffic light system needs to be equipped with a short-range communication beacon that transmits its state, and the system in the vehicle with a corresponding receiver, and processing capability.

Compared to physical infrastructure measures, speed assistance has some clear advantages. It has more extensive and homogeneous effects on speed and thereby on traffic safety. It also largely avoids negative effects in terms of land use, emissions and fuel consumption. Moreover, dynamic speed assistance provides a plausible perspective for mitigating the congestion problem.

It has been shown by simulation studies that dynamic speed limits could help to prevent, mitigate or eliminate traffic jams and shock waves, by adequate control of speed, density and flow [16]. Congestion can be dissipated by raising the outflow [17], by limiting the inflow to a traffic jam or shock wave [18,19] or by homogenising the general traffic flow [20,21]. All studies are based on the use of variable speed limit signs and static speed assistance [22,23]. However, the speed resolution of the variable speed limit signs is very coarse, and these signs are generally not obeyed very well. Dynamic speed assistance, also in the sense that it would temporarily change from warning to control mode in a motorway situation, could address this, and could also greatly improve the effect of speed assistance on the homogeneity of the traffic flow when needed. The models to be applied are quite complicated, and it would require fully automated floating vehicle data collection and processing, a position dependent dynamization of the speed limit, and provision of this information to the vehicle. Transmission is best done locally, by means of short-range communication. Extensive field operational testing of such a system would be necessary, and could provide a platform for large-scale real world testing of traffic flow models. Obligatory lane keeping in dense traffic conditions could also contribute to reducing congestion, but is difficult to implement with current technology.

Integration of navigation with speed assistance, based on a platform with a central map server and vehicle positioning unit, could offer the potential for a viable mass market solution. The technology is state-of-the-art and could be deployable in the short term. Fiscal measures and lower car insurance premiums may contribute to foster acceptance if authorities decide for voluntary introduction. However, authorities could also choose obligatory introduction, as a better tool for speed limit enforcement. Such a platform, if also equipped with an ADAS interface, could also be used by other ADAS functions as well as for road pricing applications and the motor vehicle ‘black box’.

CORE TECHNOLOGIES: POSITIONING AND COMMUNICATION

Positioning and communication are core technologies for collision avoidance, intersection support and lane keeping. Different options are available, and these can be combined in different ways to create autonomous systems and co-operative systems. For both technologies we will first provide a short review of currently available alternatives. Available in this context does not necessarily mean available ‘off-the-shelf’; it means that the concepts currently exist. Some of these concepts are mature, but most are in need of considerable improvement by further research and extensive implementation testing, since they do not currently meet fundamental requirements regarding robustness, including reliability, permanent and fail-safe operation, and few or no false alarms. A further important variable is whether such systems are used in a warning or control mode, or a combination of both. And for the warning mode the choice of the HMI is a key factor. Another issue is sensor fusion, to improve robustness, reliability and operation permanence. It is also important to distinguish collision avoidance

between two (or more) vehicles, and between a vehicle and (one or more) vulnerable road users (VRUs).

For positioning, two different concepts may be distinguished. Relative positioning determines the position and velocity (speed and direction) of the vehicle relative to the road infrastructure and to other objects (stationary and moving), by using some kind of imaging sensor and image processing. Suitable sensors for this include radar (radio detecting and ranging), lidar (light detecting and ranging), and visible light and infrared imaging. Active sensors (radar, lidar) measure the reflections of signals that were first transmitted by the same sensor. Optical and infrared sensors are generally used (in automotive applications) in a passive sense, by measuring the radiation that is naturally transmitted by objects, although they may be used in an active mode by preceding illumination of objects. Another relative positioning method is the use of magnetic lane markers. Absolute positioning uses satellite positioning, preferably in combination with inertial sensors and map data, to provide both absolute position and velocity. Relative positioning sensors are used in the first place in autonomous solutions, while the use of absolute positioning for collision avoidance requires bi-directional communication to notify the vehicle's position and velocity as well as to acquire position and velocity data of other nearby vehicles. Relative positioning may be used to avoid both vehicle-vehicle encounters and vehicle-VRU encounters. Absolute positioning is not, however, appropriate to avoid the latter type of collision.

Relative Positioning

Different types of radar are being used or investigated for automotive applications. ACC systems that are already on the market use frequency modulated continuous wave (FMCW) long-range radar (LRR, range up to 150 m) in the 76 GHz millimetre-wave band. Ultra wide band (UWB) pulse operated short-range radar (SRR, range up to 50 m) in the 24 GHz centimetre-wave band is proposed and tested for automotive applications [24]. SRR is at current prices cheaper by a factor of 40 per unit than LRR [25], is smaller and penetrates bumper materials better, which makes it easier to implement several (or an array) of such sensors in a vehicle. However, in Europe serious regulatory issues need to be resolved, and it is even debated if 24 GHz is the best solution. A large number of car manufacturers and system suppliers united in the SARA (Short-range Automotive Radar frequency Allocation) group is strongly promoting global harmonisation and regulation for this type of radar, especially for the use in applications to enhance road safety [26]. Radar is insensitive to bad weather and environmental conditions, but it cannot 'see' the (course of the) road.

Lidar imaging uses a highly directional beam of laser light in a scanning mode. It is less expensive than radar and easier to package. However, it is sensible for poor visibility, especially rain and snow, as the width of the light beam is less than the size of water droplets. Furthermore, dust, mud and snow on the car can easily block lidar beams [27].

Visible image processing for automotive applications has been pursued since the late 1980s, with a boost following the Prometheus project in the early 1990s [28]. Although good progress has been made, prices of the necessary equipment have fallen and stereo imaging makes distance determination possible, it is proving difficult to make the systems robust and sufficiently discriminatory with respect to different types of objects. Bad weather and adverse ambient conditions may drastically reduce the performance of these systems, while their operation during night-time may also be problematic. A clear advantage compared to radar is that vision systems in principle (dependent on clear road markings or other well visible road char-

acteristics) are able to distinguish the road. Therefore it is obvious, for certain applications, to integrate radar and vision systems. Infrared sensors in principle can add night-time vision capability and better penetrate bad weather conditions.

In general, the application of these remote relative positioning sensors to detect road traffic hazards in complex traffic situations is more problematic, in terms of response time, accuracy and reliability, than their use for measuring less critical phenomena like general traffic flow conditions [29].

Absolute Positioning

Current stand-alone, code-based global satellite positioning (GPS) allows a horizontal accuracy of about 10 m, and in combination with inertial sensors and a digital map of about 5 m. Performance of GPS may be improved by differential corrections. A Wide Area Augmentation System (WAAS) like the European Geostationary Navigation Overlay System (EGNOS) may be a solution for pan-European use of ITS applications, although accuracy will not be better than about 2 m. Also the signal of the geostationary satellite may sometimes be blocked, much like the signals of the GPS satellites themselves may be temporarily blocked by buildings (the urban canyon), foliage, mountains or in tunnels. In a navigation system these satellite outages are covered sufficiently by the inertial sensors (relative positioning) and the digital map. More precise carrier-phase based positioning would be possible (to the centimetre level in combination with differential corrections), but the resolution of the initial cycle ambiguity parameters takes time, and each cycle slip (discontinuity in the carrier-phase measurements due to a temporarily blocked satellite signal) means that this process has to start again [30]. Galileo plans to provide a safety related service of 4 m or better horizontal accuracy (95%) based on dual-frequency measurements [31]. As a conclusion it can therefore be said that sub-meter positioning using satellite technology in moving vehicles seems difficult to achieve. Use of a position with sub-meter accuracy would require a map database of similar or better accuracy, of which the economical feasibility has yet to be demonstrated [32]. A proposed solution to cover satellite outages is the use of pseudolites (local augmentation) [30], but it is questionable if this is cost-effective and useful if sub-meter level positioning is not possible.

Communication

Two different scenarios of medium distance communication are envisaged for road safety and traffic management applications: vehicle-to-vehicle (v2v) communication, using peer-to-peer, self-organizing ad hoc mobile radio networks (distributed, multi-hop), and vehicle-to-infrastructure (v2i), using master-slave, infrastructure centralized, one-hop mobile networks between vehicles and fixed roadside beacons [33-35].

The medium proposed for this type of communication will use the IEEE 802.11a R/A (Roadside Applications) protocol, a variant of the Wireless LAN (Local Area Network) standard, in the 5.9 GHz band adjacent to the DSRC (Dedicated Short-Range Communication) spectrum, and is developed as application M5 (Microwave 5 GHz) of the CALM architecture (Continuous Air interface for Long and Medium distance) in the framework of ISO TC204/WG 16 [36]. The v2i links are intended to support a wide range of applications (including multimedia, entertainment and Internet access), and must therefore support high data transfer rates. Stated data rates are 54 Mbps up to 80 m and 6 Mbps up to 1000 m [37]. A number of issues still need to be resolved and first-generation devices are expected in 2005, and full capability

devices by 2010. An advantage of using the 5 GHz spectrum is that it can penetrate walls and propagate around corners. This development was initiated in the USA, but has been adopted by the ITS community world-wide, although Europe has been remarkably slow in taking up this approach [37]. The eSafety final report [12] recommends, for example, identification and where necessary development of new specifications for interfaces and communication protocols for v2v and v2i communications, but does not reference CALM M5. In Europe, research on cooperative systems in general is in its infancy, but may get a boost with two large EU funded Integrated Projects on cooperative systems being prepared and expected to start early 2006: SAFESPOT with a focus on traffic safety applications, and Cooperative Vehicle Infrastructure Systems (CVIS), with a focus on traffic efficiency.

COLLISION AVOIDANCE

Much research is ongoing on the development of autonomous sensing systems for the car with the aim of both avoiding collisions and mitigating the impact of collisions once they cannot be avoided. An ultimate configuration is a 3608 car surround sensing system (providing a 'virtual safety belt') with an approximate number of 10 SRR units per vehicle for luxury cars for all kinds of functions, including crash mitigation [25,26] and one LRR unit at the front side of the car, possibly combined with video image processing, for crash avoidance.

Clearly, from a perspective of replacing infrastructure measures that are meant to be all encompassing, such systems would only contribute sufficiently at high market penetration rates. Given the regulatory problems with the 24 GHz UWB systems, and the recent decision of the European Commission to limit market penetration of such systems to 7% until 30 June 2013, to accommodate expected interference problems, and no further implementation in new cars after that date [38], it may be doubted if these systems will play an important role in traffic safety until 2010. For LRR and vision, the implementation scenario is different, although here the cost of the system may be prohibitive to induce a large market penetration before 2010.

Relevant aspects of these sensor technologies have been studied in recent years by several EU funded projects, which are presented here as examples. The RadarNet project implemented one multi-beam narrow-angle 77 GHz radar for detection up to 150 m, and an array of four 77 GHz single-beam radar sensors for a range up to 25 m, for an urban rear-end collision avoidance system for vehicle speeds up to 80 km/h. Use of 77 GHz technology was seen as an advantage, as it is the same as used for ACC [39]. The SAVE-U project developed a near-by sensing system for VRUs, for speeds up to 40 km/h, which combined passive infrared and visible spectrum imaging and a network of several parallel 24 GHz radar sensors, to make it robust in all weather and lighting conditions. Human obstacle recognition was improved by use of a large database of VRU images [40]. The CARSENSE project combined information from laser, radar, visible spectrum imaging and the vehicle dynamics sensors in a system for low-speed driving assistance in complex urban situations [41].

Of course these projects highlight only a fraction of the research into such systems that is undoubtedly in progress by car manufacturers, in co-operation with system suppliers. Nevertheless one cannot escape the conclusion that these and similar projects are still very much in the experimental stage, and need follow-up projects in order to develop systems that are really robust and have an acceptable cost price.

Cooperative systems provide another approach, at least conceptually, for rear-end collision avoidance, by use of vehicle positioning and v2v communication. In order to make this work

in a robust manner, both the communication and the positioning need to be robust and of high accuracy. Although the standards work on the M5 application in the CALM framework is in progress, it still has some way to go, and - as noted earlier - its adoption in Europe may take even longer. But it is to be anticipated that M5 based v2v communication can eventually be progressed to a state of maturity and robustness. For the vehicle positioning it is maybe a different matter. On a multilane road such a system should provide lane discrimination: in which lane is the vehicle and where in that lane? This would require a horizontal accuracy of about 0.3 m, which, as stated before, is difficult to achieve. Even if this could be achievable, a high precision digital map would be required, of which the practical and economical feasibility is yet to be demonstrated. Only a system using magnetic lane markers would be able to provide the requisite precision.

The EU-funded project CARTALK2000 investigated a cooperative longitudinal control system, using positioning based on differential GPS and inertial sensors, and an ad-hoc mobile communication network based on UMTS terrestrial radio access network (UTRAN) technology [42]. The limited set-up of the work, in view of the original plans, using only three vehicles, and concentrating on the 'transparent front' vehicle, is another indication that it is still a long way before such systems will be mature and ready for large-scale implementation. Also, for this type of application, follow-up projects may be necessary, and practical use is not to be expected before the end of this decade. In Germany, the FleetNet project developed position-based routing in vehicular ad-hoc networks [43], and the follow-up project Network on Wheels (started in 2004) tries to increase robustness and reliability of the methods in real-world radio environments, including cities.

INTERSECTION SUPPORT

In the US extensive research has been carried out on infrastructure-based cooperative intersection collision avoidance systems [44,45]. Also autonomous and v2v cooperative approaches may be used for collision avoidance at intersections. The reliability of autonomous systems will be hampered, more than for longitudinal collision avoidance, by the fact that an unobstructed line of sight, a *conditio sine qua non*, is sometimes not available. Therefore a cooperative approach seems to be the better option. Performance may be enhanced, but also complexity and cost increased, by an integration of autonomous and cooperative solutions. Like for collision avoidance, also for intersection support systems large-scale market availability at affordable prices of both autonomous and co-operative solutions before the end of the decade may be questioned. For the longer term a cooperative system for intersection support could be envisaged that goes a step beyond mere collision (hazard) avoidance, and operates in an intersection negotiation mode. In Japan research has been carried out on v2v and v2i communication based intersection support [46].

The cost-effectiveness of intersection support is doubted. For instance, red-light running accounts for the vast majority of the more than one million annual collisions at signalled intersections in the USA, which cause over 500,000 injuries, several thousand fatalities and related costs of about US$7 billion annually [47]. Speed is a crucial aggravating factor in intersection collisions. Intersection support could be one of the countermeasures, but would hardly contribute to a better protection of VRUs (pedestrians and cyclists). Speed assistance enhanced with a function to control vehicle speed at any intersection, and with beacon augmentation to avoid red-light running, might well bring more significant safety effects, as it takes into account VRUs as well, reduces the consequences of speed, and all of this with a much simpler system layout. Moreover it may help to counteract congestion in metropolitan areas by reduc-

ing variation in vehicle speeds, thereby making traffic flows more homogeneous.

LANE KEEPING

Much of the ongoing lane-keeping research and development relates to lane keeping on motorways and to the prospect of future autonomous vehicle guidance on such roads. Certainly a reliable lane-keeping system for motorways can have particular safety benefits, but the focus in this paper is on lane keeping for two-lane single carriageway roads for through traffic, as these contribute significantly to traffic unsafety. For such roads it has been proposed (for instance in the Netherlands) to implement physical lane separation everywhere, prohibiting overtaking and avoiding midline crossing due to inattention. However, the costs of this measure have proven to be prohibitive.

Lane keeping based on absolute positioning would require a horizontal accuracy of about 0.3 m, which, as stated before, seems difficult to achieve. A system based relative positioning by video cameras and line recognition is very dependent on the quality of the line(s) on the road, and not sufficiently reliable in adverse weather, lighting and ambient conditions. Such a type of system is available on the market, both for trucks (MAN, DC) and cars (Citroën).

Another method of relative positioning, based on magnetic lane markers, was developed in the USA [48], initially for autonomous vehicle guidance. However, it could provide a feasible and cost-effective alternative for safety related lane keeping on single carriageway through roads, with sub-decimetre lateral accuracy. Magnetic position markers are installed under the road surface at the lane centreline, at regular distances, typically 1-2 m, and the lateral position of the vehicle with respect to the centreline is determined by magnetic sensors in the vehicle. A similar type of lane marker system uses passive radio frequency multiplier position markers, also under the centreline, that reflect micropower radio waves transmitted from the vehicle. Tests in Japan showed that both systems can provide a lateral positioning accuracy of 4 cm or better at speeds between 20 and 120 km/h [49]. Of course such systems require an infrastructure component, which brings additional cost, but a clear advantage is that their operation is independent of weather, lighting and ambient conditions. Also, the equipment in the car is relatively inexpensive, and the durability and lifetime of the infrastructure component is high. A third method in this category is based on magnetic tape, which can be used in combination with the normal white lane markers, which nowadays are often also applied in the form of tape instead of by traditional painting. Painting in itself is cheaper, but tape lasts longer, making it overall more attractive. Magnetic tape has also been tested extensively for snowplough guidance [50].

CONCLUSION

Of the various technologies that have been discussed in this paper, navigation is mature and speed assistance options are in development, pointing the way to large-scale implementation. However, complete and up-to-date coverage of speed limits in digital map needs to be established. In general, the introduction of integrated speed assistance and navigation may reduce the need for and urgency of the various other systems that are being developed, as most safety effects could be achieved cost-effectively by these two integrated systems. Furthermore, they may establish a platform in the vehicle for future integration of other ADAS applications, as well as contribute to traffic flow improvement. Other technologies that are mature and could easily be widely applied are lane keeping by use of magnetic line marking and computer vision.

The other technologies discussed (based on radar, laser, video imaging, communication and/or satellite positioning) are promising and can also contribute to traffic safety, but need considerable improvements in robustness, reliability and cost. The difficulties do not only relate to the sensor technologies that are being employed but also to other design parameters, like the algorithms for reliable detection of VRUs. Systems based on v2v communication and vehicle positioning seem conceptually to be the most promising, although they do not take into account VRUs.

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