51. Intelligent Vehicles

Alberto Broggi, Alexander Zelinsky, Michel Parent, Charles E. Thorpe

This chapter describes the emerging robotics application field of intelligent vehicles – motor vehicles that have autonomous functions and capabilities. The chapter is organized as follows. Section 51.1 provides a motivation of why the development of intelligent vehicles is important, a brief history of the field, and the potential benefits of the technology. Section 51.2 describes the enabling technologies for intelligent vehicles to sense vehicle, environment and driver state, work with digital maps and satellite navigation, and communicate with intelligent transportation infrastructure. Section 51.3 describes the challenges and solutions associated with road scene understanding – a key capability for all intelligent vehicles. Section 51.4 describes advanced driver assistance systems, which use robotics and sensing technologies described earlier to create new safety and convenience systems for motor vehicles, such as collision avoidance, lane keeping, and parking assistance. Section 51.5 describes driver monitoring technologies that are being developed to mitigate driver fatigue, inattention, and impairment. Section 51.6 describes fully autonomous intelligent vehicles systems that have been developed and deployed. The Chapter is concluded in Sect. 51.7 with a discussion of future prospects, while Sect. 51.8 provides references to further reading and additional resources.

51.1 Why Intelligent Vehicles?

An important field of application of robotics has emerged in the last 20–25 years which is centered on the automobile, named *intelligent vehicles*. The automobile has been one of the most important products of the 20th century. It has generated an enormous industry and has given individuals a freedom of movement that has completely changed our ways of living. Indeed, the automobile has been a key factor in the large change in the way our urban societies are structured. Today, there are more than 800 million vehicles on the planet and this number is expected to double in the next ten years. This challenge has led to the development of an active research domain with the ultimate goal of automating the typical tasks that humans perform while driving. An intelligent vehicle is defined as a vehicle enhanced with perception, reasoning, and actuating devices that enable the automation of driving tasks such as safe lane following, obstacle avoidance, overtaking slower traffic, following the vehicle ahead, assessing and avoiding dangerous situations, and determining the route. The overall motivation of building intelligent vehicles has been to make motoring safer, and more convenient and efficient.

51.1.1 Brief History

The history of intelligent vehicles has developed over the last two decades. Although the first ideas were born in the 1960s, the level of maturity of the technology at that time did not allow pursuit of the original goal of implementing fully autonomous all-terrain all-weather vehicles. The first documented prototypes of automated vehicles were fielded by a few groups in the military arena in the mid 1980s [51.1–3]. The initial stimulus that triggered these innovative ideas was provided by the military sector, which was eager to provide complete automation to its fleet of ground vehicles.

It was not before the 1980s that this interest was transferred to the civil sector: governments worldwide launched the first projects, which supported a large number of researchers in these topics. The interest of the automotive industry in developing real products was only triggered after feasibility studies were successfully completed and the first prototypes were demonstrated. Testing of autonomous vehicles on real roads in a real environment was one of the most important milestones in the history of intelligent vehicles. This happened in the mid to late 1990s. Figure 51.1 shows the first motor vehicles that pioneered the development of intelligent vehicles. In the summer of 1995, the Carnegie Mellon Navlab group ran their *No Hands Across America* experiment [51.4]. They demonstrated automated steering, based solely on computer vision, over 98% of the time on a 2800 mile trip across the United States. Later in 1995 the Bundeswehr Universität Munich (UBM), Germany fielded a vehicle that was demonstrated with a 1758 km trip from Munich to Copenhagen in Denmark and back. The vehicle was able to drive autonomously for 95% of the trip. The car suggested and executed maneuvers to pass other cars. Unlike later robot cars, this car located itself on the current road and followed it until instructed otherwise. It did not localize itself in global coordinates and could drive without Global Positioning System (GPS) and road maps as found in a modern automotive navigation systems. The car's trunk was full of transputers and ad hoc hardware. A different approach was followed by VisLab at the University of Parma within the Argo project: the passenger car that was designed and developed was based on a low-cost approach. An

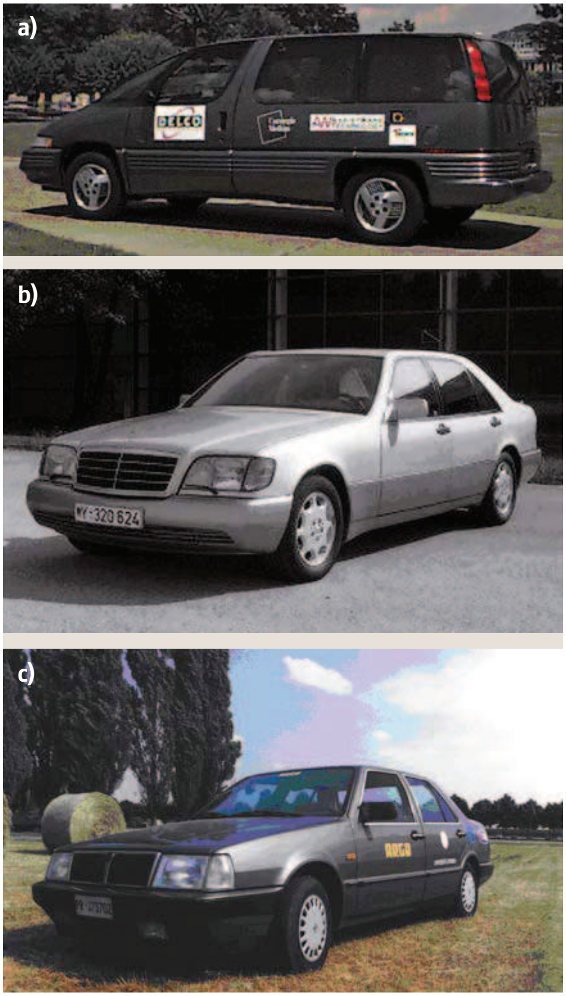

Fig. 51.1a–c Pictures of pioneering autonomous vehicles, from *top* to *bottom*: **(a)** NAVLAB, **(b)** UBM, and **(c)** Argo vehicles

off-the-shelf Pentium 200 MHz personal computer (PC) was used to process stereo images obtained from low-cost cameras installed in the driving cabin. The vehicle was able to follow the lane, locate obstacles, and – when instructed – change lane and overtake slower vehicles. The main milestone of this project was the successful test of the Argo vehicle in a tour of Italy of more than 2000 km called 'Millemiglia in Automatico' in which the vehicle drove itself for 94% of the total distance.

Current research initiatives are oriented towards the development of intelligent vehicles in realistic scenarios. However, due mainly to legal issues, full autonomy has not yet been set as the ultimate goal: the automotive industry has set as its primary goal the need to equip vehicles with supervised systems and – more generally – advanced driving assistance systems (ADAS) instead of automatic pilots. In other words, the driver is still in charge of running the vehicle, but the drive is monitored by an electronic system that detects possibly dangerous situations and reacts by either warning the driver in due time, or taking control of the vehicle in order to mitigate the consequences of the driver's inattention. Given the aforementioned legal issues, the ultimate goal has shifted towards driving assistance systems since complete vehicle automation was not felt to be a primary strategic area of investment for automotive industries. Concurrently, Departments of Transportation worldwide have been primarily interested in social, economic, or environmental objectives aimed at enhancing fuel efficiency, road network usage, and improving quality of life in terms of mobility [51.5].

Fig. 51.2a–e Grand Challenge Vehicles **(a)** Stanley (1st) **(b)** Sandstorm (2nd), **(c)** Highlander (3rd), **(d)** Kat-5 (4th) and **(e)** Terramax (5th)

The good results obtained by ADAS in the automotive arena in recent years has induced the military sector to give a new vigorous push to the original ideas of automating its fleet of ground vehicles. The Defense Advanced Research Projects Agency (DARPA) launched the Grand Challenge in 2003, a race for autonomous vehicles that had to travel for more than 200 km in unstructured environments. This unprecedented challenge attracted a large number of top-level research institutes, who worked with the million-dollar prize in mind and helped the scientific community take a considerable step forward.

In 2005 the DARPA Grand Challenge required autonomous driving in a rough terrain desert scenario with no traffic, obstacle types known in advance, and few if any road markers on a course predefined by 2935 GPS points. Five cars (maximum speed 40 km/h) completed the 211 km desert course:

1. Volkswagen of Stanford (Stanley 6 h 54 min)
2. Hummer of CMU (Sandstorm 2.5% slower)
3. CMU's second Hummer (Highlander 5% slower)
4. Gray team (Kat 5 8% slower)
5. Terramax truck (44% slower)

Figure 51.2a–e shows photographs of the five finishing vehicles. Refer to [51.6] for the technical details of the DARPA Grand Challenge.

51.1.2 Benefits of Intelligent Vehicles

Having intelligent vehicles running on our road network would bring a number of social, environmental, and economical benefits. An intelligent vehicle able to assess the driving scenario and react in case of danger would allow up to 90% of traffic accidents that are caused by human errors to be eliminated, saving human lives. According to the World Health Organization an estimated 1.2 million people worldwide are killed each year, and about forty times this number injured, due to traffic accidents.

At the same time, vehicles able to drive at high speeds and very close to each other would decrease fuel consumption and polluting emissions; furthermore they would also increase road network capacity. Vehicles communicating with a ground station could share their routes and be instructed to reroute in order to maintain a smooth traffic flow. Vehicles that can sense and obey speed limits or traffic rules would reduce the possibility of misinterpretation and antisocial driving behavior.

Fully automatic vehicles would also offer a higher degree and quality of mobility to a larger population, including young, old, or infirm individuals, reducing the need even for a driving licence. Finally, the availability of vehicles that could drive themselves would increase the quality of mobility for everyone, turning personal vehicles into taxis able to pick up people and take them to their final destination in total safety and comfort, dedicating the driving time to their preferred activities.

However, this full application of intelligent vehicles is far from being complete, since unmanned vehicles technology is still under development for many other applications. The automation of road vehicles is perhaps the most common everyday task that attracts the greatest interest from the industry. However, other domains such as agricultural, mining, construction, search and rescue, and other dangerous applications in general, are looking to autonomous vehicles as a possible solution to the issue of the ever-increasing cost of personnel. If a vehicle could move autonomously on a field to seed, or enter a mined field, or even perform dangerous missions, the number of individuals put at risk would drastically decrease and at the same time the efficiency of the vehicle itself would be increased thanks to a 24/7 operational schedule. The key challenge for intelligent vehicles is safety; accidents must not occur due to automation errors and there is zero tolerance to human injury and death.

This chapter focuses on road and traffic applications of intelligent vehicles, which are catalyzing the interest of the automotive industry, car makers, and providers of automotive technologies.

51.2 Enabling Technologies

The basic sensing and actuation technologies for intelligent vehicles are readily available on the market. The key challenge to integrating new technologies is heavily dependent on the control strategies associated with the sensor data processing and reasoning. Automated systems must consider all subsystems in a vehicle, including the interaction of the technology with the driver. Key drivers for the new technologies in an intelligent vehicle are the desired applications. Solutions are developed on the premise that the system must satisfy the requirements of the application with the minimum level of technology.

Intelligent vehicle applications require the following:

- The position, and kinematic and dynamic state of the vehicle
- The state of the environment surrounding the vehicle
- The state of the driver and occupants
- Communication with roadside infrastructure or other vehicles
- Access to digital maps and satellite data

Position localization is a key technology for intelligent vehicles. The position of the vehicle must be known if the vehicle is to be controlled along a particular trajectory. To control an intelligent vehicle to perform applications such as collision avoidance or automatic lane changing requires knowledge of the kinematic and dynamic states of the vehicle. Standard robotics techniques for position, kinematics, and dynamics are used in intelligent vehicle applications (see Chap. 34). Encoders are mounted on the steering column and the tail shaft. Vehicle heading, speed, and acceleration can be computed from the encoders using standard techniques (see Chap. 20).

To execute the trajectories in an intelligent vehicle a number of techniques are used. In many current applications of fully automated vehicles, the trajectories are fixed with limited choices at intersections. To execute the trajectories, the vehicles simply follow markers such as an antenna (a wire carrying an alternating current), magnets or passive transponders such as radio frequency identification (RFID) tags that are imbedded in the road or simple painted lines. In more advanced navigation systems, the vehicle generates trajectories in a map stored in its memory and localizes itself with respect to this map in order to execute them. This localization can be done using absolute positioning through a combination of global navigation satellite systems (GNSS), vehicular kinematic state, and inertial navigation. Alternatively, position localization can be done by relative localization using local markers such visual landmarks. (For specific reference to earlier mobile robot landmark navigation see Chap. 36.)

In order for the vehicle to execute trajectories, it needs to control the speed and the steering of the

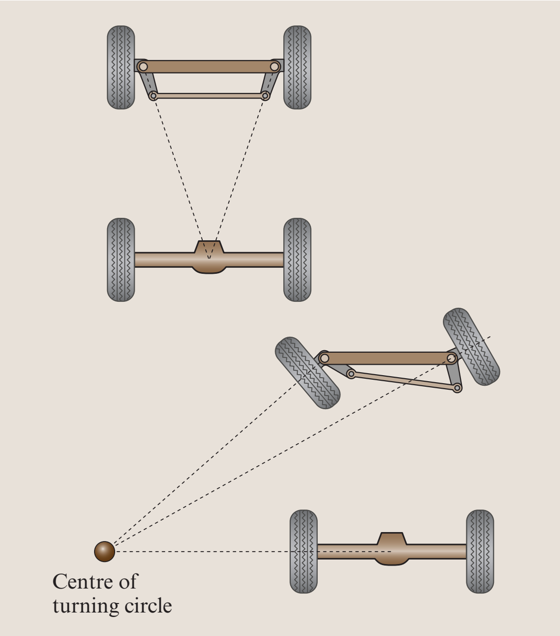

Fig. 51.3 Ackerman steering model

vehicle. Modern vehicles now incorporate electronic control units to control the acceleration (motor torque and possibly gearbox and clutch), the braking (electric or electrohydraulic brake control) and the steering angle (electric power assistance), and it is therefore quite easy to implement trajectory control of the vehicles [51.7]. The safety of these critical functions remains a challenge, and is usually solved through redundancies in the sensors, actuators, and control units.

51.2.1 Environment State

Sensing the state of the environment surrounding the vehicle is a critical aspect of intelligent vehicle applications. The most difficult function for intelligent vehicles is road scene understanding. This includes locating key landmarks: the road, other vehicles, pedestrians, traffic signals, road signs, and other unstructured obstacles. A more difficult challenge is speed control following the detection of event in the road scene. The common sensors are infrared [51.8], ultrasound [51.9], radar [51.10], laser range finders [51.11], and computer vision [51.12], which continually scan the environment as shown in Fig. 51.4. Radar is generally used for obstacle detection at a distance, while infrared and ultrasound are used for close proximity obstacle detection. Laser ranging and image processing are used to more robustly recognize the road scene under various weather conditions. Certain road scene conditions such as road signs and traffic lights can only be understood using vision sensing. Sensor fusion is commonly used in intelligent vehicle applications, particularly between monocular vision and radar/laser sensors. This work is principally being done by the tier 1 automotive suppliers (Bosch, Denso, Del-

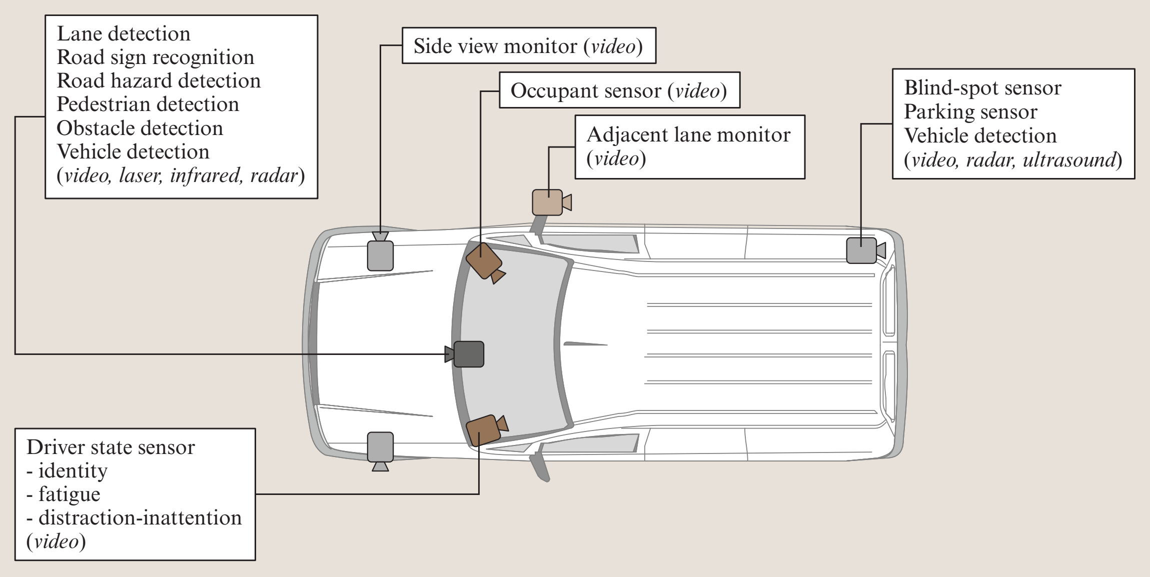

Fig. 51.4 Environment state sensing

phi, Visteon, Siemens, NEC) in cooperation with the major automotive manufacturers.

Using such sensors it is possible to map the environment surrounding the vehicle and then, using techniques such as simultaneous localization and mapping (SLAM) (Chap. 37), generate the complex manoeuvres needed for parking or for obstacle avoidance.

51.2.2 Driver State

Additionally an intelligent vehicle needs to understand the driver state, if it is to give appropriate warnings or need to take action. Vision sensors [51.13] can monitor a driver's attentiveness and fatigue by observing the direction of the driver's gaze and eyelid behavior. In an emergency knowing the position of the driver's head can assist in the safe deployment of airbags. Also, after an accident, observing the state of the driver and other occupants could be useful for the dispatch of emergency services to the accident scene.

51.2.3 Communication

Communication technologies enable interesting intelligent vehicles applications. Allowing vehicles to communicate with each other and with the highway offers the possible to create vast improvements in the safety and efficiency of the road system. Applications include intersection collision avoidance, emergency braking, and sharing of road and traffic condition information.

The basic communication modes are distinguished as

- vehicle to/from roadside infrastructure
- vehicle to vehicle

Dedicated short-range communications (DSRC) have been set up to from the vehicle to infrastructure communications to support traveler information, commercial applications (toll/parking fee collection, in-vehicle advertising), and safety applications (intersection collision avoidance, approaching emergency vehicle warning, rollover warning) [51.14].

DSRC is a wireless protocol specifically designed for intelligent transportation systems. It is a subset of RFID technology, working in the 5.9 GHz band (US) or 5.8 GHz band (Japan and Europe). It is generally implemented with a dedicated protocol, uses short messages, and works in direct line of sight over short ranges (200–300 m).

For vehicle-to-infrastructure communications, a communication protocol architecture is currently being specified by the ISO [51.15], in the technical committee 204 working group 16 [51.16]. This protocol architecture is known as continuous air interface long and medium range (CALM) [51.17] and is being implemented in Europe under the cooperative vehicle infrastructure systems (CVIS) integrated project [51.18]. CALM is based on IPv6 protocols developed by the Internet engineering task force (IETF) [51.19] , particularly the network mobility (NEMO) protocol, which allows sessions to be maintained between an in-vehicle Internet protocol (IP) network and the Internet backbone using any type of available media (3G, general packet radio service (GPRS), Wi-Fi, WiMax, M5, DSRC, satellite, etc.). For vehicle-to-vehicle applications, systems that support ad hoc networking are still in early stages. A vehicular ad hoc network (VANET) is a form of mobile ad hoc network (MANET) to provide communications among nearby vehicles and between vehicles and nearby fixed infrastructure equipment using direct and multi-hop intervehicular communication. Most of the research issues of concern to MANETs are of interest in VANETs, but the details differ. Rather than moving at random, vehicles tend to move in an organized fashion. The interactions with roadside equipment can likewise be characterized fairly accurately, and most vehicles are restricted in their range of motion, for example, by being constrained to follow a highway. The major work in this area is being supported by a series of workshops organized by Association of Computing Machinery (ACM) Special Interest Group on Management of Data (SIGMOD) [51.20].

Interaction between NEMO and the MANET or VANET is also under investigation but is not yet officially dealt with by any standardization body.

51.2.4 Digital Maps and Satellite Data

Combining GPS with stored digital maps creates a wide variety of intelligent vehicle applications [51.21]. Map data can greatly assist in the problem of road scene interpretation, map data can improve lane detection quality, help deal with the problems when sensors such as cameras do not work, e.g., in sunlight at dusk or dawn. Digital maps are widely used in commercial navigation systems for route guidance [51.22]. Such systems will be improved if real-time updating of the map occurred from traffic information [51.23]. Additional functionalities to be added include curve approach warnings [51.24], curve speed control [51.25], traffic sign information, and speed limit information [51.26].

51.3 Road Scene Understanding

Perception plays a key role in any robotic application. In the case of intelligent vehicles, the perception task is referred to as road scene understanding. It involves using different sensors (described in Sect. 51.2.1) combined with automatic reasoning, in order to create a synthetic representation of the environment around the vehicle. The knowledge base accumulated by this task is then used either to issue warnings to the driver in the case of advanced driving assistance systems (ADAS) or to control vehicle actuators in the case of complete autonomous driving. A complete and precise description of the state of surrounding environment is the key factor that allows the reduction of the number of false and missed alarms and provides the basis for smooth automatic driving. Needless to say, the perception of an outdoor environment – even if partially structured – is a challenging problem not only due to the intrinsic complexity of the driving environment itself, but also due to the impossibility of controlling many environmental parameters. Figure 51.5 shows examples of day/night, sun/streetlight illumination, temperature, poor visibility, rain/snow, and different meteorological conditions, which in general are impossible to control and have to be faced by sensing devices.

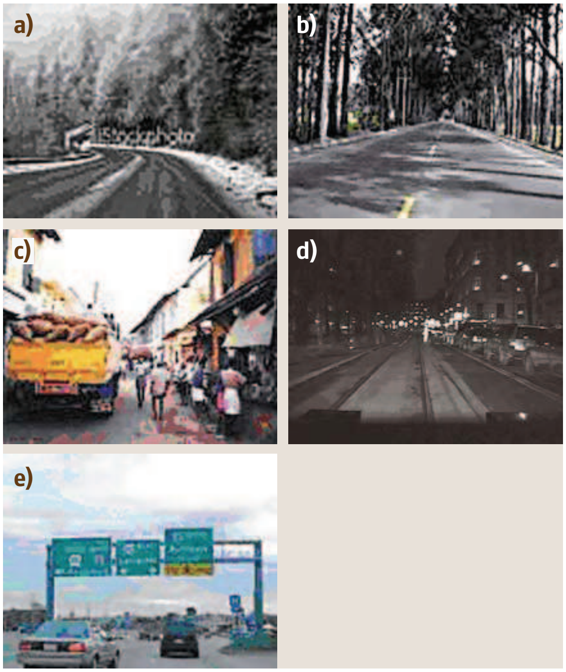

Fig. 51.5a–e Typical range of road scenes that intelligent vehicles must handle

The research community is addressing the issue of providing vehicles with robust and precise perception of the state of the environment from two different perspectives. One approach is to provide vehicles with ever-increasing sensing capabilities and processing power aimed at the provision of powerful onboard intelligent systems; Daimler-Chrysler is a world leader in this area [51.27]. An alternative approach is to use road infrastructure as an active component capable of communicating with all vehicles and sharing information on road conditions in real time [51.28]. Indeed these two perspectives can also be merged to provide a mixed solution to safely control a vehicle and in dynamic environments [51.28].

The task of road scene understanding may be addressed differently, depending on the availability of an intelligent infrastructure and on other players exhibiting cooperative behavior. The task of understanding the state of the environment can be simplified through the availability of information coming from other sources, thereby limiting the need to perform a robust and complete sensing onboard each vehicle. Helpful information could come from the infrastructure itself (for example, road conditions and geometry, number of lanes, visibility, road signs, or even real-time information such as traffic-light status or traffic conditions) or other players (such as the presence of the vehicle with precise position, speed, and direction). The players may also carry real-time information gathered by and shared with other players.

Although research is currently focussed on both intelligent vehicles and intelligent infrastructures, the first generation of production intelligent vehicles will have to rely primarily on their own sensing capabilities since the availability of information coming from other sources such as the infrastructure and other vehicles will take a while to be deployed in real-world situations. In fact, in order to be of practical use, intelligent roads must cover a large proportion of a country, and simultaneously cooperative intelligent vehicles must also be sufficiently widespread. It is important to note that the investment in intelligent infrastructures and intelligent vehicles comes from different sources: mainly from governmental institutions for the former, and vehicles owners for the latter.

The information that is owned by the infrastructure itself and that could be made available to the vehicles includes

- precise geometry of the lane/road
- road signs
- status of traffic lights

On the other hand, the infrastructure can also assess and deliver real-time data such as

- road conditions
- visibility
- traffic conditions

Another important piece of information that needs to be gathered by intelligent vehicles is the presence of other road players, such as

- vehicles
- vulnerable road users (pedestrians, motorcycles, bicycles)

Although it could be assumed that sometime in the future all vehicles will be equipped with active systems that allow them to be safely avoided by other vehicles, it is quite improbable that pedestrians and bicycles will have similar equipments: their presence will need to be detected using onboard sensors only. The same consideration also applies to obstacles that may unexpectedly be found on the road, or to temporary situations such as roadworks: if a vehicle needs to cope with the unexpected, then it needs to have the capability to assess the situation in real time with its own sensors.

This is why onboard sensing is of paramount importance for future transportation systems; vehicle-to-vehicle and vehicle-to-infrastructure communications may help and improve the sensing, but a complete sensor suite must also be installed on our future vehicles. The main challenges in road environment sensing are examined below.

51.3.1 Road/Lane Tracking

Many vehicles prototypes have been equipped with lane detection and tracking systems, starting from the very first implementations in the early 1980s [51.1–3]. Indeed in this case computer vision plays a basic role; although generally the road can also be detected with laser scanners [51.11], the only generic technology able to detect lane geometry and lane markings with high precision is computer vision. Most lane tracking approaches have focused on detecting lane markings and exploiting structure in the environment, such as the parallelism of the left and right lane markings, the invariance of road width, or the widely used flat-road assumption. These assumptions were mainly used to overcome the problem of having a single camera (a choice driven by cost). Some systems use stereo vision to detect lane markings and are able to work without such constraints. The problem of lane tracking in highway situations is basically a solved problem – with commercial systems being deployed in passenger and commercial vehicles [51.29]. An example of the typical output of a commercial lane tracker is shown in Fig. 51.6.

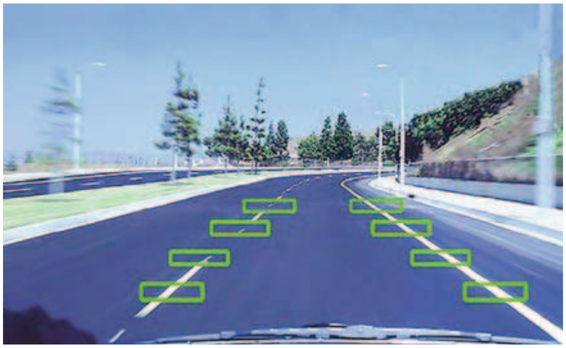

Fig. 51.6 Lane detection

However, such systems cannot guarantee that lane detection systems will work with 100% reliability; these systems typically work with 95–99% reliability. Therefore, lane tracking systems are only being used in lane departure warning systems since no failures can be tolerated for autonomous driving. Efforts are underway to develop algorithms that will tolerate a variety of driving conditions, and push the 100% reliability boundary [51.30].

51.3.2 Road Sign Detection

Another fairly straightforward use of computer vision is road sign detection and understanding. Road signage is deliberately structured to aid human drivers. Road signs use a set of well-defined shapes, colors, and patterns. The signs are placed at consistent heights and positions in relation to the road. Therefore reading road signs is an achievable task for computer vision. Detection is done using a collection of shape and/or color detection schemes [51.31,32]. After the detection and localization phase, recognition takes place. Normally this task is performed by pattern-matching techniques such as image cross-correlation, neural networks, or support vector machines since the possible set of road signs is limited and well defined. Figure 51.7 illustrates the con-

Fig. 51.7 Road sign detection for speed warning application

cept of a speeding warning system based on speed sign detection. The challenge for research work in this area lies in the robustness of detection and the reliability of classification of signs. Most automotive companies have systems under development, e.g., Siemens [51.33].

51.3.3 Traffic-Light Detection

Color and pattern matching are also the key techniques used for the detection of traffic lights [51.34]. Although the detection of traffic lights is not overly complex, this application hides one further aspect that makes vehicular applications difficult: besides the correct localization and recognition of a signal, special care has to be taken in checking the signal position and orientation on the road/lane since that signal may not be addressed to the current vehicle. This is particularly true in downtown intersections at which many traffic lights are visible at the same time; in this case the vehicle must have the capability to select the correct traffic signal that must be obeyed. Some experiments have been undertaken with active traffic signals, able to emit the status of the traffic light using radiofrequencies [51.35]. This involves additional infrastructure; at this stage vision seems to be the only simple viable solution.

51.3.4 Visibility Assessment

One of the key challenges is detection of fog. The meteorological visibility distance is defined by the International Commission on Illumination (CIE) as the distance beyond which a black object of an appropriate size is perceived with a contrast of less than 5%. Different techniques for measuring this parameter – and thus detect foggy conditions – have been implemented [51.36]. Although many of the methods use vision, there are also efficient alternatives – generally used in fixed locations such as airports and traffic-monitoring stations – based on the use of multiple scattering lidars. The main challenge of using vision to estimate visibility is that a moving vehicle generally cannot rely on a specific reference point/object/signal at a specific distance.

51.3.5 Vehicle Detection

The detection of vehicles has been addressed using a large variety of sensor technologies, ranging from vision to lidars, from radars to sonars.

Despite being different in shape and color, vehicles share the same characteristics and feature a large size and reflective material. The position of vehicles is predictable once a rough indication of the road/lane position is available. Vehicles, in fact, can be successfully detected by many different sensors independently [51.37–39]. Figure 51.8 shows a vision-based vehicle detection system.

Nevertheless, although the solution to this problem seems straightforward, each sensor has its own domain of application and its own challenges. Vision is generally powerful, but may fail in low visibility and bad-illumination scenarios (night or tunnels) or in heavy traffic conditions when vehicles may occlude each other. Vision in the infrared domain (thermal imaging) is able to detect vehicles with a high confidence since vehicle tires and mufflers generally exhibit high temperatures and are therefore easily detected in the image. However, parked vehicles, trailers, and even vehicles which have just started to move are colder than running vehicles and therefore less visible. Lidars are generally robust, but have decreased sensitivity in adverse weather condi-

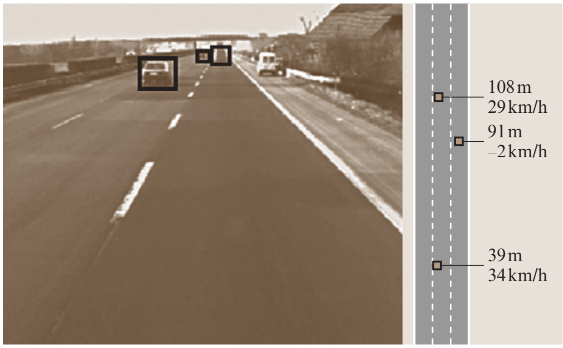

Fig. 51.8 Vehicle detection – lane and range position

tions. Radars, while cheap, can suffer from bias in lateral measurements due to the presence of other nearby reflecting objects. Finally sonars are applicable only for very short distances. The research challenge is to implement multisensor fusion robustly. A common approach is to fuse vision with radar [51.40].

51.3.6 Pedestrian Detection

The detection of vulnerable road users (pedestrians and bicycles) is one of the most difficult tasks for intelligent vehicles. The appearance of a pedestrian is challenging: a pedestrian shape can change greatly within a few tens of milliseconds, there are no clear invariants in color, texture, or size, and no assumptions can be made about posture, speed, or the visibility of parts of the human body such as the head. Machine learning methods have been successfully applied to this problem [51.11, 27, 31, 41]. Greater reliability and reduction in false alarms have been achieved through the incorporation of stereo vision [51.42]. However, the detection of vulnerable road users is one of the most relevant research topics worldwide since a great number of benefits – including insurance reductions – may be achieved once a fully functional pedestrian detector is available on cars. Countermeasures may be activated to reduce the consequences of vehicle–pedestrian accidents, such as the firing of external airbags or the opening of the hood to lessen the impact of a head-on collision. Currently, with all possible technologies under evaluation, no solution seems to offer reliable detection in every scenario: radars are not able to detect pedestrians reliably in crowded scenarios, while vision has the many drawbacks listed above. Even thermal imaging, which – although still very expensive – is generally believed to be one of the most promising technologies, fails in some situations, such as hot summer days and, in general, in high-temperature environments.

51.4 Advanced Driver Assistance

Given the legal liabilities and technical challenges of achieving 100% reliability for autonomous intelligent vehicles, it appears likely that motor vehicles will have pieces of autonomous functionality added progressively and that cars will eventually evolve into autonomous robots. The perception techniques described earlier can be used in a variety of ways to make driving safer, more efficient, and less demanding. Individual perception techniques, or combinations of sensing modes, are being used to provide warnings to drivers of dangerous situations. These warnings are being used to prevent collisions in a variety of situations, such as when backing up, when leaving a roadway, into rear ends, on lane changing/merging, with pedestrians, and at intersections.

Developing a collision warning system requires many steps beyond building the perception system. For a typical example, roadway departure warning, the steps followed in a program initiated by the US National Highway Traffic Safety Administration include:

1. Statistical studies: In the United States, crashes involving a single vehicle leaving the roadway are relatively rare, but disproportionately dangerous; approximately 40% of the 40 000 fatal crashes per year in the US are single-vehicle crashes where the vehicle leaves the roadway. The first part of the study looked at the prevalence of those crashes, and determined that this would be a good type of crash to prevent.
2. Causal factors: The second step was to determine the causes of those crashes. Most run-off-road crashes are due to driver factors such as excessive speed, inattention, or loss of control. This is an important observation, because it means that alerting the driver, or warning of difficult situations, could prevent those incidents. For the fraction of crashes caused by mechanical failure a warning system would not be useful; in this type of crash, mechanical failure is involved in less than 5% of the crashes.
3. Opportunities for intervention: This part of the study set out to determine whether a warning system could be effective, and, if so, how far in advance the warning would have to be given. Given typical road departure trajectories, typical widths of roads and shoulders, and the range of potential steering responses, this task generated requirements for how accurately the system would have to track vehicle trajectory in order to predict a roadway departure.
4. Human factors: Since the system being designed is a warning system, rather than an active control, it is crucial to understand what kinds of warning a driver (who may be distracted or sleepy) would respond to, and how quickly and accurately the response will

be. Reaction times vary widely across individuals: using one second for reaction time is a fairly standard estimate.

5. Simulator studies: A driving simulator is like an aircraft flight simulator for cars or trucks, with a variety of simulated roads and conditions. Simulator studies were used to test driver response to warnings: directional or nondirectional audio warnings, steering wheel shakes, and combinations. A nondirectional audio cue worked best.
6. System specification development: Based on the preceding steps, in order for a system to be useful, it needs to work at day and night, in almost all weather conditions, needs to measure vehicle speed, lateral position relative to the road, lateral heading, and roadway curvature, and predict future vehicle trajectories long enough in advance to trigger a warning alarm.
7. Perception and system development: Given those specifications, there are several ways that a perception system could be built to sense the road and the vehicle's trajectory relative to the road. For this particular test, a lane keeping system – rapidly adapting lane position handler (RALPH) was developed and tuned [51.43].
8. Limited tests: The entire system – sensors, processing, driver interface – was built and tested with a limited number of volunteers, and the system tuned and validated.
9. Full-scale operational tests: The system was deployed in test fleets, including long-haul trucks and passenger cars.

51.4.1 Collision Avoidance and Mitigation

The complete cycle from the idea of using perception to prevent crashes, to full system development, took over 10 years in this case. The pure *robotics* part of the system is a crucial element, but is only one piece of the development needed to make a useful product. Some active control has already been assumed by today's vehicles. Antilock brakes have been on the market for many years. Traction control systems which control throttle to stop wheel spin are being introduced. Electronic stability control systems take this the next step further, controlling throttle and individual wheel brakes to help in cornering performance. So, gradually, people are willing to cede some control to very reliable automated systems. We can expect this trend to continue.

Each collision warning type has its own list of specific development challenges, as described below.

Backup Collisions

The sensing challenge is to see relatively small objects, such as fence posts or children's toys, while not picking up false alarms from pavement joints or leaves and debris. The sensors used in today's commercial vehicles are piezoelectric ultrasonic sensors, which are inexpensive [51.9]. However, ultrasonic sensors have well-known limitations. The challenge of developing low-cost, accurate, reliable sensors remains.

Rear-End Collisions

These are among the most difficult collisions to prevent, with the most challenging sensing conditions. Rear-end collisions often happen at high speeds, requiring long-distance sensing of other vehicles (up to 100 m at US highway speeds, much longer at the high speeds found on some European roads or for the longer braking distances needed for heavy trucks). That in itself is not too demanding a challenge: the sensed objects in this case are relatively large and have high metal components, so radar and lidar are both feasible sensing modes. The biggest range-sensing challenge is sorting out true targets (slow or stopped vehicles) from false targets (overhead signs or bridges, and side lobes from strong reflectors on the side of the road). It is also important to determine if the sensed vehicle is in the same lane as the smart car, or a different lane. Sensing lane markings at such a large distance is a very difficult challenge; merging lane sensing (often done by vision) with obstacle sensing (by a different sensor) and registering the two to within the resolution of a lane is a daunting task. This technology remains under development through industry and government programs [51.44].

Lane-Change/Merge Collisions

In the simplest case, the countermeasure to this kind of collision involves short-range sensing to cover the *blind spots* on the rear corners of a vehicle, where it is difficult to see with mirrors. For passenger cars, this area is quite small, and can be covered with a single sonar or radar. Often, the user interface is a warning light placed in the rear-view mirrors [51.45]; this reinforces good driver behavior of checking mirrors before changing lanes. The sensing challenge for heavy trucks or transit buses is the same as for cars, except that the area not visible in planar mirrors can be much larger. Figure 51.9 shows examples of blind-spot detection for cars and heavy vehicles.

The usual solution is a row of sensors along the side of the vehicle, although scanning lidars or panoramic vision are also used in some experimental applica-

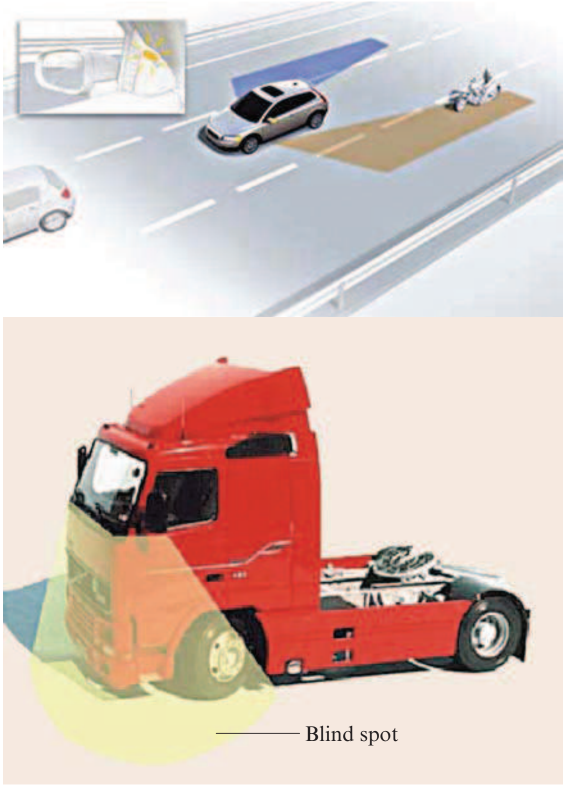

Fig. 51.9 Blind-spot detection

tions [51.46]. The further complication for lane-change warnings is in high-speed driving, where it is important to look not just adjacent to the vehicle but a long way to the rear, to find overtaking vehicles with high relative speeds. Recently a commercial product has been brought to market [51.47].

Pedestrian Collisions

Pedestrians are particularly important to detect, because pedestrians are much more vulnerable than people in vehicles; as discussed earlier they are also unfortunately relatively difficult to detect and very hard to predict. Just detecting a pedestrian is not sufficient. In transit operations, for instance, a bus operates close to pedestrians much of the time. To do meaningful collision warning, it is important to detect the pedestrian, detect their current path, look for cues such as crosswalks or curb edges that modify the probability of the pedestrian's trajectory, and match all of these factors with the predicted trajectory of the vehicle. It is crucial to tune the warning system to produce few false alarms while not missing real alarms. A particularly dangerous situation is pedestrians slipping and falling underneath a bus: these are very dangerous situations, but very difficult to detect in time to warn the driver. For these reasons, automotive manufacturers have worked on products such as night vision to enhance driver perception [51.48].

Intersection Collisions

Intersection collisions are particularly difficult to prevent because they often involve challenging sensing scenarios. Many of these collisions involve occluded vision, with lines of sight blocked either by large vehicles or by adjacent buildings. They also often involve high closing rates from oblique angles, making it necessary to see a long distance with a very wide field of view. The solution usually proposed is to add intelligence to the infrastructure, either in fixed sensing (such as radars looking down each approaching road) or in some kind of radio relay that takes data from approaching smart cars and passes it to other approaching vehicles. None of these solutions is particularly attractive: the large number of intersections makes it difficult to envision any universal solution.

Other Obstacle Collisions

Vehicles have collisions with many things other than other vehicles and pedestrians: animals (deer, dogs, cats), car parts (tire carcasses, rusted-out exhaust systems), cargo that falls off of trucks, construction debris, etc. Warning drivers about these kinds of objects on the roadway is a challenging task. A piece of construction timber on the roadway may be large enough to do significant damage to a car, but be small enough to be difficult to see, and be invisible to radar. Some interesting work has been done with high-resolution stereo vision [51.49], with polarimetric radar [51.50], and with high-resolution scanning laser range-finders [51.51]. However, in general this remains a difficult problem.

Other Actions

Besides warning the driver, there are other actions that an intelligent vehicle can take short of assuming control. If a collision is inevitable, particularly from the side of the vehicle where there is limited crush space, the system can brake and deploy airbags even before physical contact. Of course, such a system would have to be nearly 100% reliable. More simply, if the system senses an imminent front collision, it can preload the power brakes, saving fractions of a second in brake reaction time. The driver must still actuate the brakes, but the onset of hard braking can be much quicker. At 100 km/h, a 0.1 s saving in braking actuation saves approximately 3 m of stopping distance, which can be the difference between a severe rear-end collision and a much lighter crash. Such systems are being introduced into the high-end market by all the major automotive manufacturers.

Collision Avoidance

The next step beyond emergency braking is an automated system. Such systems have several advantages over a human driver: much quicker reaction times, access to sensors such as individual wheel speeds and slips plus external sensors such as radars or lidars, access to individual brake controls and other controls, and so forth. So, if the system had ideal situational awareness, it could in many cases do a better job of avoiding a collision than a human could. This is still a very difficult area for implementation, however. First of all, the human has access to higher-level knowledge: the driver may be watching the behaviors of other cars, may make eye contact with pedestrians or drivers, may be watching a policeman directing traffic, etc. So it may be that a manoeuvre that, to the system, looks like the best way to prevent the collision, is actually the wrong action to take. Secondly, in most countries, as soon as the vehicle takes control there is a shift in the liability for any resulting crash from the driver to the manufacturer. So there is a great reluctance to take active control. An alternative approach recently developed is to observe the environment state with lidar, and monitor the dynamic vehicle state to determine whether the accident is unavoidable. If the driver can no longer take corrective action, that is, brake or turn away safely, then emergency braking occurs [51.11].

For now, however, active collision avoidance remains a research area, with significant questions of reliability, human factors, and liability.

Combining perception with control gives partial automation for specific tasks, such as adaptive cruise control, lane keeping, assisted parking, and slow driving in stop-and-go situations.

51.4.2 Adaptive Cruise Control

Adaptive cruise control (ACC) is the logical extension of standard cruise control to also include keeping a safe distance from the preceding vehicle. If there are no vehicles in front of the smart car, it follows a set speed, as with standard cruise control. If a slower-moving vehicle is in front, an ACC-equipped car will sense the vehicle using radar or lidar, and slow to maintain a safe distance (typically set to a 1.5–2 s following gap). Figure 51.10 shows an illustration of the ACC concept. The sensing challenge for ACC is much easier than the challenge of rear-end collision countermeasures, since ACC systems are only designed to deal with other moving vehicles.

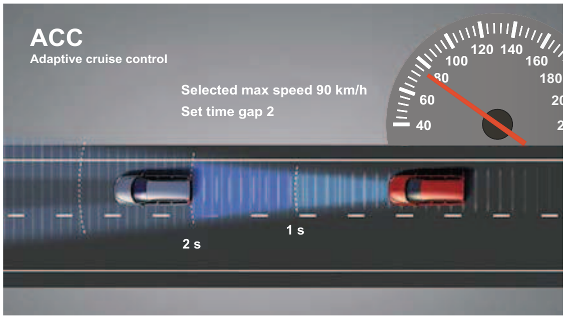

Fig. 51.10 Advanced cruise control (ACC)

The biggest sensing difficulty for rear-end collision countermeasures is separating stopped vehicles on the road from objects off the road; for ACC this difficulty is bypassed by ignoring all stopped objects. Moving objects are classified as in-lane or out-of-lane based on a number of heuristics. Often, the smart car's own steering radius is used as an estimate of the road curvature ahead, in order to determine whether vehicles ahead are in the same lane. Since the systems are explicitly sold as *convenience* instead of *safety* systems, they only need to deal with normal situations with relatively low differences in velocity, and they leave the more difficult situations up to the human driver. The human is still alert, controlling the steering, and watching the traffic. These systems are being introduced by all the major car manufacturers.

51.4.3 Stop and Go

Stop-and-Go driving assistance (also referred to as low-speed ACC) is at the opposite end of the speed spectrum, when vehicles are creeping along in dense traffic. At slow speeds, it is easy to track the vehicle ahead, and to move when it moves, steer when it steers, and stop when it stops. If the traffic accelerates to a modest speed, the stop-and-go system disengages, and the human must assume control of the throttle, brake, and steering. Since the speeds are very slow and the distances are short, many different sensing systems will work such as stereo vision, radar, and lidar [51.52, 53].

51.4.4 Parking Assist

Parking assistance is also a low-speed aid. In a typical scenario, the driver initiates the system by pushing

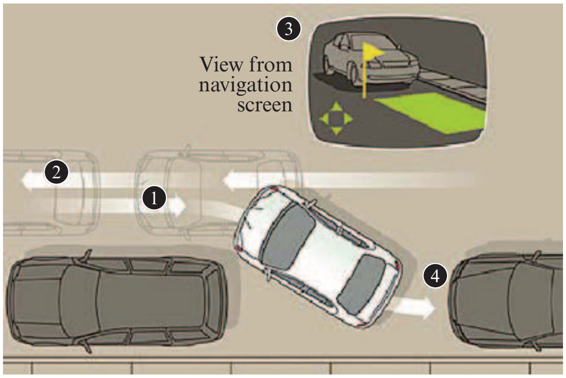

Fig. 51.11 Parking assistance

a button when driving past an empty parking space. The system measures the length of the space using odometry, measures the positions of the cars in front and in back using short-range sensors, and infers the position of the curb by assuming that the surrounding cars are standard-sized cars parked near the curb [51.54]. Figure 51.11 illustrates parking assistance.

Once the system is fully engaged, it takes over steering, planning and executing the ideal parallel park steering sequence. In some systems, the human is still responsible for throttle and brake, again insuring that the human is alert, watching for encroaching pedestrians or other obstacles. Such a system has been introduced by Toyota [51.55].

51.4.5 Lane Keeping

Lane keeping assistance is the natural extension to road departure warning systems. Given a lane tracking system, it is straightforward to add control of the steering wheel to keep the vehicle centered in its lane [51.1–3]. This has a number of uses. Some cities would like to run transit buses on narrow roadways, for instance the shoulder of highways or through narrow streets in old cities. Automated lane keeping systems using mechanical guideways are in use in several places [51.56]. It is easier and less expensive if such systems can be electronic rather than relying on specially installed mechanical guides. A specific subcategory is precision docking: for a transit bus to pick up a passenger in a wheel chair, either the bus must deploy a special ramp (which is a slow process), or it must pull up to a level dock and leave a very small gap, so that the wheel chair can safely roll on or off. Short-range precision docking systems use either a downward-looking sensor, looking at painted lines or magnetic markers, or a sideways sensor looking at the curb or dock, in order to guide the bus to its parking spot. Finally lane-keeping assistance is a convenience for driving on highways, especially with gusty winds. Honda has released a vehicle equipped with both lane-keeping assistance and ACC [51.57]. The danger with such systems is that the driver no longer has an active moment-to-moment role, and may lose concentration or even fall asleep. These systems are not designed for full automation, and still require a driver to handle unusual circumstances. The next stage is to integrate driver state monitoring. If the driver is inattentive then all automatic systems are disengaged.

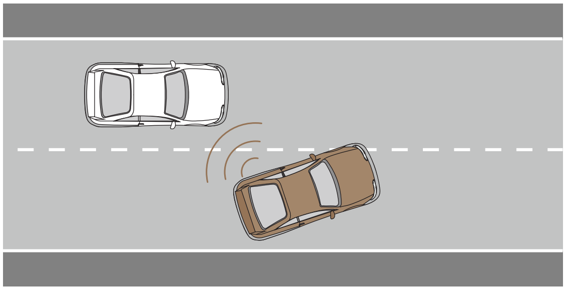

Fig. 51.12 Lane changing – side detection

51.4.6 Lane Changing

Lane changing assistance is the next extension in partial autonomy. It combines lane keeping and ACC with blind-spot monitoring. If the car can safely overtake a vehicle, then a lane change is undertaken and speed is unchanged. Otherwise, the ACC slows the vehicle down. At its simplest such a driver assistance system can advise a driver whether a lane change can be safely undertaken [51.58]. In its most advanced form the lane change is undertaken completely automatically by the vehicle [51.1]. Such systems require an additional side-facing sensor, typically radar (shown in Fig. 51.12)

51.5 Driver Monitoring

There has been an evolution of thought regarding the role of the driver in intelligent vehicles. The grand goal has been to replace the driver with a fully automated system. As discussed earlier, full automation of intelligent vehicles is still some years away due to system reliability and legal liability reasons. The next step in the development of the motor vehicles is partial automation – where individual autonomous functions such as ACC, lane keeping, lane changing etc. are developed. Motor vehicle designers have realized that the driver cannot be removed from the vehicle, and must instead be supported by systems onboard a motor vehicle. Over 92% of motor vehicle accidents are caused by driver error [51.59]. It is likely that the next generation of intelligent vehicles will work in the following way.

1. The vehicle will monitor the road scene using advanced driver assistance system technologies discussed earlier to assess the state of the environment and warn the driver of dangerous situations, e.g., lane departure warnings.
2. The vehicle will also monitor the driver using vision sensors to assess the state of the driver. If a driver is fatigued, drowsy, inattentive, distracted or under the influence of drugs then accidents can occur. The vehicle warns the driver of dangerous circumstances, e.g., drowsiness warning.
3. For legal liability reasons intelligent vehicles will not take control, rather the driver will be alerted using visual, audio, or tactile warnings. The vehicle will not perform collision avoidance; rather collision mitigation will occur through emergency braking.
4. If an accident is unavoidable the vehicle can autonomously apply emergency braking. To maximize the safety of the occupants in the vehicle, seatbelt restraints are tightened and airbags are safely deployed.
5. After an accident has occurred knowing the state of the driver and the passengers is important. If an occupant has been injured a call to the emergency services can be dispatched automatically by the vehicle.

In all the steps described above monitoring the driver is critical. For future advanced driver assistance systems (ADAS) to work safely the driver should be put in the loop, for example, in a lane departure warning systems, it is not possible to determine whether a vehicle departing from a lane due to cause by driver intention or error. If the state of the driver is being monitored, and the system can detect that the driver's eyes are closed or the driver is looking away from the road, then it can be inferred that the lane departure was involuntary and that a lane departure warning should be given to the driver. For ADAS to be accepted by drivers the systems should not give false warnings. If the driver is looking directly at the road then lane departure warnings should not be given (or a different subtle warning should be given). Similarly more sophisticated systems such as lane keeping should not be engaged unless the driver is fully attentive and has their hands firmly on the steering wheel. The key point is that drivers must be fully engaged with and in control of the driving task. This is a most important consideration in the design of ADAS for intelligent vehicles.

Combining perception with control gives partial automation for specific tasks, such as adaptive cruise control, lane keeping, assisted parking, and slow driving in stop-and-go situations.

51.5.1 Driver Fatigue, Inattention, and Impairment

By directly monitoring the driver using visual sensing opens up the possibility of developing a new class of ADAS applications. It is possible to monitor driver state through monitoring signals such as an electrocardiogram (ECG), temperature etc. However, market studies by automobile manufacturers have shown that people do not like any wires, or gadgets attached; driver monitoring must be noncontact and noninvasive. The only solution is to use vision as the sensing medium. The technical challenge to develop a computer vision system that can automatically detect a driver of any age, sex, race, with/without eye or sunglasses, and with/without facial hair is enormous. Recently significant progress has been made with systems being developed that can also detect where a person is looking (gaze direction) [51.13].

Once the driver's state (head position, eye gaze, eye blink rate) can be measured then ADAS applications

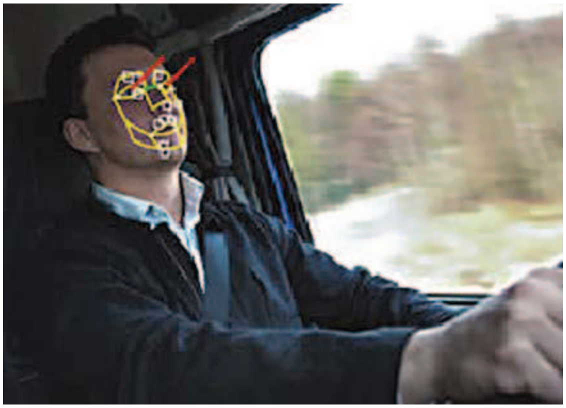

Fig. 51.13 Driver state detection

can be developed. Figure 51.13 shows the output of a commercial driver state detection system.

Driver Impairment

Safety authorities estimate that as many as 50% of all road accident fatalities are caused by driver impairment due to alcohol or drugs [51.60]. Recent research has shown that driver impairment can be detected by sensing abnormal scanning patterns of eye gaze. It promises to open up a new class of ADAS. There have been major education and legislative initiatives in many Organization for Economic Cooperation and Development (OECD) countries, resulting in a significant reduction in road fatalities. However, the difficult cases (fatigue, distraction, and inattention) have become more prominent. ADAS technologies could have a significant impact in further reducing the road toll.

Driver Fatigue

Safety authorities estimate that 25–30% of all road fatalities are caused by driver fatigue [51.61,62]. Research has shown that there are four visible factors that indicate the onset of fatigue – prolonged eye closure, uncontrolled head moments, drooping eyelids, and reduced eye-gaze scanning. Systems are under development that focus only on eye closure [51.63]; the challenge of fusing all four factors together into a robust algorithm that works for a wide range of drivers remains an open research problem.

Driver Inattention

Safety authorities estimate that up to 45% of all traffic accidents – from minor dents to serious incidents – are caused by driver inattention or distraction [51.64]. Research has shown that if the drivers consistently keep their eyes on the road then driving becomes a much safer experience [51.65]. All major automotive manufacturers are developing ADAS applications that warn the driver if they are distracted from the driving task. More sophisticated ADAS under development use the driver's gaze direction to check whether safe driving practices are being followed, for example, did the driver check the side mirror before a lane change was performed? If the driver fails to check the side mirror a warning would be issued.

Driver Workload

The increase in new electronic systems and gadgets that are being installed into today's motor vehicles is also another source of distraction. Questions arise about when and under circumstances should a driver change a compact disc (CD) or answer a phone call. Research is underway into the development of workload systems. These systems take into account the vehicle state (speed, acceleration, braking, gear-change yaw rate etc.) to determine whether information management tasks such as answering a phone call, sending a short message service (SMS) message are allowed [51.65]. The next stage of research is to include sate information about the road scene and the driver. If the car is driving on a country road, and the driver is attentive then distractive tasks could be allowed and managed.

51.5.2 Driver and Passenger Protection

The automotive industry is moving towards the use of active safety systems such as airbags to complement passive systems such as seatbelts. ADAS will play a critical role in active safety systems. In emergency braking or impending rear-end collision situations, seatbelts can be pretensioned and airbags primed. Drivers and passengers could be further protected through the development of smart airbags [51.66]. Airbags, while considered to be an essential part of a modern car, can cause fatalities if the occupant is too close to the airbag, is a child, or is not wearing a seatbelt. Smart airbags deploy that are dependent on the position of the vehicle occupant's head. The driver state monitoring technologies discussed earlier are an essential component of smart airbags.

51.5.3 Emergency Assistance

The speed at which people are given treatment after a serious accident is critically related to the survival rate of victims. While it is expected that ADAS will lead to a reduction in road accidents, it will not eliminate accidents. Therefore it is important that automated systems for emergency situations are developed. Systems that use GPS, vehicle state information, and mobile communication systems have been developed that send the world coordinates of the vehicle to emergency authorities after an accident [51.67]. This information can be augmented by using driver monitoring technology to assess the condition of the occupants of the vehicle. Such types of system are currently being researched.

51.6 Automated Vehicles

Intelligent vehicles that are fully autonomous can be justified for safety, traffic congestion, and environmental considerations.

51.6.1 Operating Safely

The first problem is safety. As stated earlier, automobile accidents are one of the main causes of human fatalities – on a staggering scale. This is a catastrophe of larger magnitude than all armed conflicts since the beginning of mankind. The most economically advanced countries (the OECD) have been able to reduce the number of fatalities significantly through improved technology in vehicles – improved handling, braking and passive safety. Transport infrastructure has been greatly improved; modern freeways are ten times safer than regular roads [51.68]. However, these improvements appear to be reaching a limit in terms of the number of deaths per million passengers-kilometers, particularly in industrialized countries.

As discussed earlier, motor vehicles are inherently dangerous due to their reliance on human control. Slight errors at high speeds can have catastrophic results. As discussed earlier the most common cause is driver distraction, which leads to improper reaction times or driving actions. Human error also frequently occurs while handling emergency situations. A large percentage of drivers will take improper action in such situations and produce an accident that could have been avoided by a skilled and attentive driver [51.68]. The best solution to these problems is to remove the driver from the control loop. As discussed earlier the interim step is to assist the driver to warn him/her in case of potential danger (e.g., in the case of excessive speed before a dangerous bend or when a car is present in the blind spot while changing lane), or to take over control in emergency situations (e.g., emergency braking in the case of impending collision). For legal liability reasons, until it can be shown that autonomous systems have high integrity and reliability, people must be kept in the loop – in a supervisory capacity.

51.6.2 Traffic Congestion

The success of the automobile also leads to the saturation of the road infrastructure, particular in cities. Each car needs a certain amount of space in order to operate safely. The usual width of roads is 3.5 m in order to accommodate steering imprecision, while vehicles are about 2 m in width. Spacing between vehicles also has to be kept at a safe minimum to prevent collisions during deceleration (this principally depends on driver reaction time). It is usually recommended that the spacing should correspond to a time gap of at least 1.5 s. This spacing leads to a maximum throughput of about 2200 cars per hour per lane, independent of traffic speed. This is not high if we consider that a suburban train can carry about 60 000 passengers per hour on an infrastructure of similar dimensions. Furthermore, high-density car traffic of greater than 2200 cars leads to a breakdown in traffic flow (stop-and-go traffic) and to increased likelihood of accidents, which can drastically decrease the overall capacity of system. The solution to this problem also lies in the removal of the driver from the control loop to improve lateral guidance (reduction of the width of lanes) and longitudinal control (with possible time gaps of around 0.3 s, independent of the speed) while maintaining traffic safety. Such techniques of automated driving could multiply the throughput of road infrastructure by a factor of five. This was demonstrated in particular by the work performed in the advanced highway systems (AHS) project in the United States, which led to the demonstration of seven-car platoons running at speeds up to 130 km/h on a dedicated freeway in San Diego with gaps of about 0.5 s [51.69].

Another congestion problem is associated with parking. Every individual vehicle is only used for a small percentage of its total usable life. Most of the time, motor vehicles occupy space very unproductively. Typically, a car requires about 10 m^2 of space. Usually, parking occurs at the curbside – a space that is very limited in large cities and cannot accommodate all the cars of residents and visitors. In parking lots, each car will need four times this amount in order to have access to each individual slot. If a transportation system based on fully automated cars could be developed, people would not need to own cars but could rely on a service such as the one offered by taxis with vehicles that would come on demand and offer a complement to mass transport. This is the concept of the cybercar, which is under development in Europe [51.70].

51.6.3 Environmental Factors

The ever-increasing deployment of passenger and commercial vehicles has led to critical environment problems of noise and of pollution in the local community. In addition greenhouse-gas emissions have an impact at the global environment level. Recently automotive manufacturers have been able to reduce emissions of local pollutants drastically; noise in cities is now perceived as the major problem by the inhabitants. At the global level, the generation of CO_2 through the use of fossil fuels is also considered to be a major problem that will require drastic steps. In the short term, this may lead to limiting the use of vehicles that generate CO_2 above certain levels. In the longer term, this will lead the automotive industry to offer vehicles that run on various forms of energy and to new forms of transportation systems with much higher efficiency. Automated vehicles running in platoon formations on new infrastructures could form such a system.

51.6.4 The Automobile of the Future

All three challenges are now at the heart of new policies being developed in many countries. These policies concern safety and emissions features on the vehicles with a strong push towards advanced safety systems, as was recently seen in Europe with the *Intelligent Car Initiative* [51.71]. At the infrastructure level, there is also a strong push to implement regulation schemes to limit and control the use of road transport and promote alternative and more efficient transport means. In the future, this means that the use of a private automobile will be much more regulated and more integrated with other modes of transport.

The automotive industry might move from an industry of products to an industry of service where anyone can have access to mobility in the most cost efficient way. Both mass transportation and individual transportation would be offered by companies in the most cost-efficient way, respecting local regulations. Companies operating in this service industry could be transit operators, taxi companies, car rental companies, car-sharing companies or even new entrants into the transportation business such as mobile phone companies, which are already familiar with large customer bases and mobility services. Car-sharing operators such as those operating in Germany, Switzerland, Japan, and the USA are likely candidates [51.72]. Figure 51.14 shows a commercial car-sharing operation.

Fig. 51.14 Car sharing from Toyota

Fig. 51.15 Automated electric cars from Honda

In this context, new types of vehicles such as electric ones and automated driving are being developed because of the decrease in cost of operation and improvements in safety.

Demonstration projects by Honda and by Toyota have already been put in place along these lines. However, this market is still searching for its operators and business model as well as the right products [51.70]. Figure 51.15 shows the Honda concept automated car.

There are two distinct trends in the future of automated vehicles. One is with advanced driving assistance, which has spread rapidly since the late 1990s with numerous techniques appearing recently in high-end passenger vehicles and commercial vehicles (buses and trucks). This trend has been described earlier in this chapter. The other trend is associated with the arrival of people-movers based on automated guided vehicles (small or large) in specific locations and on dedicated tracks (protected or not).

It is forecast that, in the next ten years, these two trends will merge, with individual vehicles having dual-mode capabilities: manual (with strong control and assistance) driving on regular roads and fully automatic driving on dedicated zones where no (or few) manual vehicles will be allowed, thereby ensuring smooth and safe operation of the automated vehicles [51.70]. This type of vehicle will be perfect for the implementation of mobility services with vehicles that can be called on demand (perhaps through a mobile phone) when and where needed. With the development of such zones, new dedicated infrastructures will be built specifically for these vehicles to go automatically and at high speed from one automated zone to the next. This appears to the most realistic path for *automated highways* to be realized, since it is now considered nearly impossible to have a smooth evolution from the actual infrastructure with its manual vehicles to one with a majority of fully automated ones. This is one of the reasons why the AHS project was cancelled in the USA despite a very successful demonstration in 1997.

51.6.5 Automated Vehicle Deployment

As discussed earlier some automated functions are being introduced in production vehicles. Honda and Toyota have introduced a combination of lateral control (lane keeping assistance using image processing) and longitudinal control (adaptive cruise control using laser and radar sensors) [51.57]. An intelligent parking assist system has been introduced recently by Toyota, offering the ability for the car to be parked without the driver using the steering wheel. However, this system does not use sensors: the driver has to position his/her vehicle on the image of the rear camera [51.55]. However, most car manufacturers and some component manufacturers are actively working on the sensors to remove this task from the driver.

Fig. 51.16 Toyota ABRT used in IMTS Phileas

Fig. 51.17 Cybercars at Schipohl airport, Amsterdam

Fully automated vehicles without any human intervention or supervision are now appearing in the commercial domain. Automated bus rapid transit (ABRT) combines the service quality of rail transit with the flexibility and cost of buses (as shown in Fig. 51.16). Nonautomated bus rapid transit (BRT) is already recommended by the Word Bank in developing countries as the most efficient mass transport system. By reserving a dedicated lane for bus operation and adding some light infrastructure to facilitate loading and unloading, capacities similar to those of a train (60 000 passengers/h/direction) can be obtained, as has been demonstrated in South America [51.73]. By adding the driving automation on a BRT, the system can be made more efficient and safer, as is already the case with automated metros.

The intelligent multimode transit system (IMTS) consists of vehicles guided by magnetic markers imbedded in the middle of their dedicated roads. The platoon running function (three electronically linked vehicles running in file formation at uniform speeds) of the IMTS consists of precisely controlling the speed of all the vehicles in the platoon to be the same at all times [51.74]. In the city of Eindhoven in The Netherlands, multi-articulated buses with several steering axes are also running in automated mode on a dedicated track using magnetic markers [51.75]. These ABRT usually keep a driver on the vehicle since there is the possibility of reverting to the manual mode if need be (such as for an unexpected obstacle or in situations with many pedestrians); however, future plans are for full automation.

ABRT technology can also be found with smaller vehicles, now called cybercars, for on-demand door-to-door operation [51.70]. These vehicles have been put in operation for the first time at the Schiphol airport (Amsterdam) in December 1997 to move passengers from long-term parking lots to the airport terminal (Fig. 51.17). Since this time these cybercars have been further developed, financed by the Information Society Technologies (IST) programme of the European Commission [51.70]. The long-term future of cybercars may lie with the development of dual-mode vehicles, with a particular emphasis on car-sharing operations [51.72]. Cybercars will have an automatic mode for operation in city centers (restricted to this type of vehicles) and a driver-operated (with assistance) mode for regular roads. The automobile industry is examining the viability of the development of such vehicles.

In order to match the performance of manually driven vehicles in urban environments, automated vehicles face major technical challenges. In particular, planning a trajectory for a car while avoiding moving and static obstacles remains as an important research challenge. In 2005, the DARPA Grand Challenge described at the beginning of this chapter brought together a large number of these researchers to demonstrate the feasibility of automated driving techniques. Five vehicles succeeded in completing the difficult course of 132 miles in the desert in totally autonomous mode. The next DARPA challenge in 2007 will see multiple vehicles operating simultaneously in an urban environment; this challenge will certainly bring products based on autonomous vehicle techniques closer to the market [51.76].

51.7 Future Trends and Prospects

Our cars, trucks, and buses are inevitably getting smarter. The future path is not completely known, and is likely to vary in different locations.

Several trends are clear, however. As sensor-equipped vehicles become more common, there will be increasing opportunities to build sensor-friendly technologies into roadways and into vehicles. It is straightforward to reduce the amount of radar clutter on roadsides by replacing large metal signs, which are excellent radar reflectors, with nonreflective signs made of plastic or composites. It will be desirable to make overpasses with lower radar reflectivities, either by using different materials, by coating steel structures with radar-absorbing material, or by proper geometry design. At the same time, it will be desirable to increase the radar cross-section of small vehicles, such as motorcycles, to make them easier for radar-equipped cars to detect. Radar-reflecting licence plates, for instance, would make smaller vehicles stand out more clearly.

The next steps may be to deploy systems that support the active transmission information from infrastructure to vehicle and vehicle to vehicle. Dedicated short-range communications (DSRC) is already in wide use in smart toll collection. It is easy to imagine DSRC-equipped vehicles receiving alerts from roadside sensors of upcoming fog, or ice, or congestion. Intelligent vehicles that detect unusual roadway conditions (via radar or lidar, slip detectors, or driver actions such as hard braking) could broadcast that information to all nearby smart vehicles. As market penetration of equipped vehicles increases, the value of such ad hoc communications nets will go up dramatically.

Vehicle-to-vehicle communications need not be only via radio. Light-emitting diode (LED) brake lights can be pulsed at kilohertz frequencies, well above the bandwidth at which human eyes can detect flicker, but easily received by following vehicles. This would be a straightforward way for a vehicle to tell other vehicles about the onset of hard braking, or other unusual roadway conditions.

51.8 Conclusions and Further Reading

The general public will become increasingly accustomed to intelligent systems – sensors and communications on vehicles. The only showstopper in the large-scale deployment of robotics technologies in the automobile field is the ability of the industry to deliver the technologies with total safety, which focus attention on the problems of failsafe systems and their certification. The rail and aerospace industries have solved these problems but in a very different environment. In these industries, the cost of safety for each vehicle can be much higher than in a car or a bus and the operational environment is also quite different, with professionals operating and maintaining the system. Manufacturers will slowly develop experience in reliability and cost engineering, and governments will gradually work out liability issues. For these reasons, systems that put the driver in the loop of new automation technologies will be the initial focus of development.

This technical progress still will not answer societal questions. Will smart vehicles make public transportation more efficient and desirable? Or will they make it easier for people to use their personal vehicles, since driving will be less stressful? The nature of transport, and its effect on urban areas, is not easily predictable. Intelligent transportation systems of the future will provide the tools to shape these discussions; society will have to choose its future from an increasingly rich set of alternatives.

For further reading on this topic there are a number of sources that can be recommended:

- intelligent vehicles survey text [51.77]
- intelligent transport systems journals [51.78–80]
- annual conferences [51.81–84]
- government resources [51.85–89]
- magazines [51.90]

References

51.1 E.D. Dickmanns: The development of machine vision for road vehicles in the last decade, Proc. IEEE Intelligent Vehicles Symposium 2002, Vol. 1, Paris (2002) pp. 268–281

51.2 A. Broggi, M. Bertozzi, A. Fascioli, G. Conte: *Automatic Vehicle Guidance: The Experience of the ARGO Autonomous Vehicle* (World Scientific, Singapore 1999)

51.3 C.E. Thorpe (Ed.): *Vision and Navigation: The Carnegie Mellon Navlab* (Kluwer Academic, Dordrecht 1990)

51.4 D. Pomerleau, T. Jochem: Rapidly adapting machine vision for automated vehicle steering, IEEE Expert, **11**(2) 19–27 (1996), Special Issue on Intelligent System and their Applications

51.5 US Department of Transport: Intelligent Transportation Systems, Saving Lives Through Advanced Vehicle Safety Technology: Intelligent Vehicle Initiative Final Report (2005) Publication No. FHWA-JPO-05-057. http://www.its.dot.gov/ivi/ivi.htm

51.6 K. Iagnemma, M. Buehler (Eds.): Special Issues on the DARPA Grand Challenge, J. Field Robot. **23**(8,9) (2006), www.darpa.mil/grandchallenge

51.7 L. Vlacic, M. Parent, F. Harashima: *EDS Intelligent Vehicle Technologies, Theory and Applications* (Butterworth-Heinemann, Oxford 2001)

51.8 Micron: Supplier of imaging sensors including infra-red (Micron, Boise 2007), www.micron.com

51.9 Valeo: Supplier of automotive technology – including ultrasonic parking assistance systems www.valeo.com

51.10 Hella: Supplier of automotive 24-GHz radar sensors www.hella.com

51.11 Ibeo: Supplier of automotive laser sensors www.ibeo-as.com

51.12 Mobileye: Supplier of automotive computer vision sensors www.mobileye.com

51.13 Seeing Machines: Supplier of driver state vision systems www.seeingmachines.com

51.14 Leearmstrong: Support site for Dedicated Short Range Communications (DSRC) discussions www.leearmstrong.com

51.15 Sae: ISO/TC204 Transport Information and Control Systems (TICS), Working Group 16, Wide Area Communications/Protocols and Interfaces http://www.sae.org/technicalcommittees/tc204wg16.htm

51.16 T. Ernst: The information technology era of the vehicular industry, ACM SIGCOMM Comput. Commun. Rev. (CCR) **36**(2), 49–52 (2006), http://www.acm.org/sigs/sigcomm/ccr/archive/2006/april/p49-ernst.pdf

51.17 CALM working group producing standards and specifications http://www.calm.hu and http://www.calmforum.com

51.18 CVIS: *Cooperative Vehicle-Infrastructure Systems* (ERTICO, Brussels 2007), http://www.ertico.com/en/activities/efficiency_environment/cvis.htm

51.19 ISOC: *Internet Engineering Task Force* (ISOC, Sterling 2007), http://www.ietf.org

51.20 Sigmobile: Annual series of workshops. Lastest iteration The Third ACM International Workshop on Vehicular ad hoc Networks (VANET 2006), http://www.sigmobile.org/workshops/vanet2006/

51.21 Trimble: Manufacturer of GPS navigation systems www.trimble.com

51.22 Navman: Manufacturer of in-car navigation systems www.navman.com

51.23 Ertico: actMAP an EU project for dynamic map updating (ERTICO, Brussels 2007), www.ertico.com

51.24 S. Rogers, W. Zhang: Development and evaluation of a curve rollover warning system for trucks, IEEE IV2003 Intelligent Vehicles Symposium, Columbus (2003) pp. 294–297

51.25 D. Vaughan: Vehicle speed control based on GPS/MAP matching of posted speeds, US Patent 5485161, Trimble Navigation Limited

51.26 IN-ARTE: An EU project for combining maps and sensors safety applications (Frauenhofer IAO, Stuttgart 2007), http://www.iao.fraunhofer.de/Projects/IN-ARTE/

51.27 D.M. Gavrila, U. Franke, C. Wöhler, S. Görzig: Real-time vision for intelligent vehicles, IEEE Instr. Measure. Mag. **4**(2), 22–27 (2001)

51.28 Japanese Advanced Safety Vehicle Project (Road Transportation Bureau, Tokyo 2007), http://www.mlit.go.jp/jidosha/anzen/asv/ASV_English/ASV3.htm

51.29 Iteris: Supplier of lane tracking systems www.iteris.com

51.30 N.E. Apostoloff, A. Zelinsky: Robust vision based lane tracking using multiple cues and particle filtering. Proc. IEEE Intelligent Vehicles Symposium, Columbus (2003) pp. 558–563

51.31 D.M. Gavrila, V. Philomin: Real-time object detection for 'smart' vehicles. Proc. Seventh IEEE International Conference on Computer Vision, Kerkyra, Vol.1 (1999) pp. 87–93

51.32 G. Piccioli, E. De Micheli, P. Parodi, M. Campani: Robust method for road sign detection and recognition, Image Vis. Comput. **14**(3), 209–223 (1996)

51.33 C. Bahlmann, Y. Zhu, R. Visvanathan, M. Pellkofer, T. Koehler: A system for traffic sign detection, tracking, and recognition using color, shape, and motion information. Proc. IEEE Intelligent Vehicles Symposium (2005) pp. 255–260

51.34 U. Franke, A. Joos: Real-time stereo vision for urban traffic scene understanding. Proc. IEEE Intelligent Vehicles Symposium, Dearborn (2000) pp. 273–278

51.35 Nissan safety vehicle that interacts with infrastructure (ERTICO, Brussels 2007), http://www.ertico.com/en/news_and_events/ertico_newsroom/nissan.htm

51.36 N. Hautiere, R. Labayrade, D. Aubert: Estimation of the Visibility Distance by Stereovision: A Generic Approach, IEICE Trans. Inform. Syst. **E89-D**(7), 2084–2091 (2006)

51.37 R. Labayrade, D. Aubert, J.P. Tarel: Real Time Obstacle Detection in Stereo Vision on non Flat Road Geometry through 'V-Disparity' Representation. Proc. IEEE Intelligent Vehicles Symposium, Paris, Vol.2 (2002) pp. 646–651

51.38 Z. Sun, G. Bebis, R. Miller: On-road vehicle detection: A review, IEEE Trans. Pattern Anal. Machine Intell. (PAMI) **28**(5), 694–711 (2006)

51.39 E. Segawa, M. Shiohara, S. Sasaki, N. Hashiguchi, T. Takashima, M. Tohno: Preceding vehicle detection using stereo images and non-scanning millimeter-wave radar, IEICE Trans. Inform. Syst. **E89-D**(7), 2101–2108 (2006)

51.40 T. Kato, Y. Ninomiya, I. Masaki: An obstacle detection method by fusion of radar and motion stereo, IEEE Trans. Intell. Transport. Syst. **3**(3), 182–188 (2002)

51.41 M. Oren, C. Papageorgiou, P. Sinha, E. Osuna, T. Poggio: Pedestrian detection using wavelet templates, Computer Vision and Pattern Recognition, San Juan (1997) pp. 193–199

51.42 L. Zhao, C.E. Thorpe: Stereo- and neural network-based pedestrian detection, IEEE Trans. Intell. Transport. Syst. **01**(3), 148–154 (2000)

51.43 D. Pomerleau: Ralph: Rapidly adapting lateral position handler. In Proc. IEEE Symposium on Intelligent Vehicles, Detroit (1995) pp. 506–511

51.44 US DOT: Intelligent Vehicle Initiative Program (US DOT IVI, Washington 2007), www.its.dot.gov/ivi/ivi.htm

51.45 Roadranger: Eaton-Vorad Road Ranger BlindSpotter product www.roadranger.com

51.46 L. Matuszyk, A. Zelinsky, L. Nilsson, M. Rilbe. Stereo panoramic vision for monitoring vehicle blind-spots. Proc. IEEE Intelligent Vehicles Symposium, Parma (2004) pp. 31–36

51.47 Motiontrends: Volvo S80 vehicle with advanced driver assistance systems (Motion Trends, Touluse 2006), www.motiontrends.com/2006csm/m03/volvo/volvo_s80_safety_systems.shtml

51.48 Visteon: Automotive supplier – including night vision www.visteon.com

51.49 T.A. Williamson: *A High-Performance Stereo Vision System for Obstacle Detection*, Tech. Rep. CMU-

RI-TR-98-24 Robotics Institute (Carnegie Mellon University, Pittsburgh 1998)

51.50 E. Li: Millimeter-wave polarimetric radar system as an advanced vehicle control and warning sensor. Ph.D. Thesis (University of Michigan, Michigan 1998)

51.51 J.A. Hancock: Laser Intensity Based Obstacle Detection and Tracking. Ph.D. Thesis (Carnegie Mellon University, Pittsburgh 1999)

51.52 W.D. Jones: Keeping cars from crashing, IEEE Spectrum **38**(9), 40–45 (2001)

51.53 Delphi: Supplier of automotive technology – including stop-go adaptive cruise control systems www.delphi.com

51.54 I.E. Paromtchik, C. Laugier: Motion generation and control for parking an autonomous vehicle. Proc. International Conference on Robotics and Automation, Orlando, Vol. 4 (1996) pp. 3117–3122

51.55 Toyota: Toyota parking assistance system www.toyota.co.jp

51.56 V.R. Vuchic: O-Bahn: Description and evaluation of a new concept, Advances in Bus Service Planning Practices, Transportation Research Record No. 1011, (Transportation Research Board, Washington DC 1985)

51.57 S. Ishida, J.E. Gayko: Development, Evaluation and Introduction of a Lane Keeping Assistance System. Proc. IEEE Intelligent Vehicles Symposium, Parma (2004) pp. 943–944

51.58 Siemens: Siemens-VDO lane changing assist www.siemensvdo.com

51.59 J. Treat, N. Tumbas, S. McDonald, D. Shinar, R. Hume, R. Mayer, R. Stansifer, N. Castellan: Tri-Level study of the causes of traffic accidents: Final report – Executive summary. Tech. Rep. DOT-HS-034-3-535-79-TAC(S) (Institute for Research in Public Safety, Bloomington 1979)

51.60 M. Carmen del Rio, J. Gomez, M. Sancho, F.J. Alvarez: Alcohol, illicit drugs and medicinal drugs in fatally injured drivers in Spain between 1991 and 2000, Forensic Sci. Int. **127**(1–2), 63-70(8) (2002)

51.61 N.L. Haworth, T.J. Triggs, E.M. Grey: *Driver Fatigue: Concepts, Measurement and Crash Countermeasures*. Transport and Communications, Federal Office of Road Safety, Human Factors Group, Department of Psychology, Monash University (1988)

51.62 N.L. Howarth, C.J. Heffernan, E.J. Horne: Fatigue in truck accidents. Tech. Rep. 3, Monash University Accident Research Centre (1989)

51.63 W.W. Wierwille, L.A. Ellsworth: Evaluation of driver drowsiness by trained raters, Accident Anal Prevent. **26**(5), 571–581 (1994)

51.64 J. Stutts, D. Reinfurt, L. Staplin, E. Rodgman: The role of driver distraction in traffic crashes. Tech. Rep., Foundation for Traffic Safety (AAA Washington 2001)

51.65 T. Victor: Keeping Eye and Mind on the Road. Ph.D. Thesis (Uppsala University, Sweden, 2005)

51.66 J.E. Santos Conde, M.A. Hillebrand, A. Teuner, N. Stevanovic, U. Lurgel, B.J. Hosticka: A smart airbag solution based on a high speed CMOS camera system. Internet Conference on Image Processing, Kobe, Vol. 3 (1999) pp. 930–934

51.67 Volvo: Future safety features of Volvo vehicles (Volvo Trade Corp., Göteborg 2002), http://www.volvo.com/NR/rdonlyres/6114A843-D711-4A5E-9D56-9ACD501A2289/0/MRilbe.pdf

51.68 M. Schulze, J. Irion, T. Mäkinen, M. Flament: Accidentology as a basis for requirements and system architecture of preventive safety applications, 10th International Forum on Advanced Microsystems for Automotive Applications (AAA 2006), Berlin (2006), http://ip-prevent.org/en/public_documents/publications/papers_presentations

51.69 X.Y. Lu, H.S. Tan, S.E. Shladover, J.K. Heidrick: Implementation and comparison of nonlinear longitudinal controllers for car platooningj, AVEC 2000, 5th International Symposium on Advanced Vehicle Control. Ann Arbor (2000)

51.70 Cybercar: Cybercar - Automated Bus Rapid Transit vehicle www.cybercars.org

51.71 European Commission: Intelligent Car Initiative. Communication from the European Commission. COM-2006-59 (European Commission, Brussels 2006), http://europa.eu.int

51.72 World Carshare Consortium, Paris (2007), http://www.ecoplan.org/carshare/cs_index.htm

51.73 R. Cervero: Creating a linear city with a surface metro: The story of Curitiba, Institute of Urban and Regional Development, University of California, Berkeley, IURD Working Paper 643 (1995)

51.74 H.S. Jacob Taso, J.L. Botha: Definition and Evaluation of Bus and Truck Automation Operations Concepts. Path Rep. UCB-ITS-PRR-2002-08. University of California (2002)

51.75 Phileas Bus, http://www.phileas.nl

51.76 2007 Darpa Grand Challenge (Department of Defense, Washington 2007), http://www.darpa.mil/grandchallenge/index.asp

51.77 R. Bishop: *Intelligent Vehicle Technology and Trends* (Artech House, Boston 2005)

51.78 IEEE Transactions on Intelligent Transportation Systems (ITS), Journal published by IEEE

51.79 IEEE Transactions on Vehicular Technology, Journal published by IEEE

51.80 Transportation Research PART B: Methodology, Journal by Elsevier

51.81 Intelligent Vehicles Symposium. Annual conference Sponsored by IEEE

51.82 Intelligent Transportation Systems Conference. Annual conference Sponsored by IEEE

51.83 Vehicular Technology Conference Annual conference. Sponsored by IEEE

51.84 World Congress on Intelligent Transportation Systems. Annual conference. Sponsored by ITS Societies
51.85 US Department of Transportation, ITS Joint Program Office (DOT, Washington 2007), http://www.its.dot.gov/
51.86 European Union Research on Transportation (European Commission, Brussels 2007), http://ec.europa.eu/research/transport/
51.87 Advanced Driver Assistance Systems in Europe (ADASE Daimler Chrysler, Brussels 2007), http://www.adase2.net/
51.88 Japan Ministry of Land, Infrastructure and Transport, Road Bureau ITS Program (MLII, Tokyo 2007), http://www.its.go.jp/ITS/
51.89 INVENT: A German program combining intelligent vehicles and infrastructure (BMFT, Berlin 2007), www.invent-online.de/en/projects.html
51.90 ITS Magazine, published by IEEE