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Towards Autonomous Vehicles

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MATC

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Towards Autonomous Vehicles

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16. Abstract

We are moving towards an age of autonomous vehicles. Cycles of innovation initiated in the public and private sectors have led one into another since the 1990s; and out of these efforts have sprung a variety of Advanced Driver Assistance Systems and several functioning autonomous vehicles. The challenges that face autonomous vehicle are still significant. There is still technical work to be done to make sensors, algorithms, control schemes, and intelligence more effective and more reliable. As automation in vehicles increases, the associated human factors challenges become more complex. Then, there are a host of socioeconomic issues. Are autonomous vehicles legal; and who is liable if one crashes? How can we ensure privacy and security of data and automation systems? Finally, how might the wide adoption of autonomous vehicles affect society at large? It is hoped that when they appear, they will bring with them the promised benefits of safety, mobility, efficiency, and societal change.

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List of Abbreviations

ABRT	advanced bus rapid transit
ACC	adaptive cruise control
ADAS	advanced driver assistance systems
AGT	automated guideway transit
AI	artificial intelligence
CAN	controller area network
CFL	certificate revocation list
CICAS	cooperative intersection collision avoidance system
DARPA	Defense Advanced Research Projects Agency
DATMO	detection and tracking of moving objects
DSRC	dedicated short range communications
DVI	driver-vehicle interface
ECU	electronic control unit
EDR	electronic data recorders
EKF	extended Kalman filter
EU	European Union
FCS	Future Combat Systems
FCW	forward collision warning
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FMVSS	Federal Motor Vehicle Safety Standards
FOT	field-operational test
GRT	group rapid transit
HMI	human-machine interface
HMM	hidden Markov models
IMA	intersection movement assist
IMU	inertial measurement units
ISTEA	Intermodal Surface Transportation Efficiency Act
IVBSS	Integrated Vehicle-Based Safety System
IVI	Intelligent Vehicle Initiative
LCA	lane change assist
LDW	lane departure warning
LIN	Local Interconnect Network
LOA	level of automation
LRR	long range radar
MATC	Mid-America Transportation Center
MTBF	mean time between failures
MTTR	mean time to restore
NAHSC	National Automated Highway System Consortium
NCAP	New Car Assessment Program
NHTSA	National Highway Traffic Safety Administration
NSA	National Security Agency
NTC	Nebraska Transportation Center
OBU	on-board units
OOTL	out of the loop
PDA	personal digital assistant
PRT	personal rapid transit
RSU	road-side units
RUC	road use charging
SLAM	simultaneous localization and mapping
SRR	short range radar
TPMS	tire pressure monitoring system
TRB	Transportation Research Board
UGV	unmanned ground vehicles
UKF	unscented Kalman filter
UMTRI	University of Michigan Transportation Institute
USDOT	U.S. Department of Transportation
V2I	vehicle-to-infrastructure
V2V	vehicle-to-vehicle
VII	vehicle infrastructure integration

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Abstract

We are moving towards an age of autonomous vehicles. This is not an overnight development; but has been ongoing for decades, sometimes in fits and starts, and lately with some momentum. Cycles of innovation initiated in the public and private sectors have led one into another since the 1990s; and out of these efforts have sprung a variety of Advanced Driver Assistance Systems and several functioning autonomous vehicles. Even earlier, fully autonomous transit vehicles had been developed and deployed for niche applications.

The challenges that face autonomous vehicle are still significant. Not surprisingly, there is still technical work to be done to make sensors, algorithms, control schemes, and intelligence more effective and more reliable. As automation in vehicles increases, the associated human factors challenges become more complex. There will be a period when we have automation but still require human supervision; and we cannot let the driver become complacent. Then, there are a host of socioeconomic issues, some that have already arisen, and some that are predicted. Are autonomous vehicles legal; and who is liable if one crashes? How can we ensure privacy and security of data and automation systems? Finally, how might the wide adoption of autonomous vehicles affect society at large?

On the path towards autonomous vehicles, these challenges will peak at different points; and we will find that the details change dramatically from level to level. Nevertheless, enormous progress has been made in the last few years. It is hoped that when they appear, they will bring with them the promised benefits of safety, mobility, efficiency, and societal change.

Chapter 1 Why Autonomous Vehicles?

The vision for autonomous vehicles is ambitious and compelling. It may sound like science fiction rather than a real development that could happen in our lifetimes. Yet, the possibility exists that we will see fully autonomous vehicles on U.S. roads in a scant few decades (or years). And what will their effect on society be? That is a question worth pondering.

It's also worth pointing out right at the beginning that there is a whole range of developments that will lead up to autonomous vehicles that, while not worthy of the name, still move us closer to the goal. For this reason, the National Highway Transportation Safety Administration (NHTSA) now prefers the term *automation* to *autonomous*, as it is inclusive of a range of automation levels. This report is, in large part, a study of the various modes and levels of automation that will one day result in a fully autonomous vehicle.

A radical reduction in the number of fatalities, injuries, and property damage due to crashes is a huge motivating factor in the realization of the autonomous vehicle. Motor vehicle crashes are the leading cause of death for ages 11-27, and over 32,000 people are killed each year in crashes. Additionally, there are over two million crashes with injuries and over three million crashes with property damage. On average, one person is killed every 16 minutes in a vehicle crash (NHTSA 2013a). Moreover, crash causation studies reveal that 93% of all crashes are attributable to driver error (NHTSA 2008). The safety goal of the autonomous vehicle is nothing less than a "crash-less" car (Johnson 2013).

The potential implications of autonomy for efficiency and sustainability are also startling. Driving in congested traffic can increase fuel consumption as much as 80% while increasing travel time by a factor of 4 (Treiber, Kesting, and Thiemann 2008); and it is estimated that 40% of fuel use in congested urban areas is used just looking for parking (Keirstead and Shah 2013).

On the other hand, allowing cars and trucks to travel in closely spaced platoons reduces aerodynamic drag and can increase fuel efficiency as much as 15 or 20% (Manzie, Watson, and Halgamuge 2007). Then there's this: in a crash-less environment, there is no reason for most cars to be as massive as they are. Many transportation needs can be satisfied by very light vehicles (James and Craddock 2011; Goede et al. 2009). This is the start of a virtuous cycle, allowing powertrains, brakes, and other systems to also be downsized.

Our overall mobility stands to benefit greatly from automation and the eventual autonomous vehicle. Higher traffic densities can be sustained on highways due to platooning, and shorter trip times will be realized by preventing traffic congestion. Autonomous vehicles will afford personal mobility to the elderly, the disabled, the young, and others who cannot drive for some reason.

Other ramifications for society at large are harder to predict, but could be just as impressive. The average car sits at home in the garage or is parked in a lot for 22 hours per day. Instead of owning a vehicle that sees so little use, an autonomous shuttle could be summoned to pick you up for your daily commute to and from work. The whole concept of car ownership would be shifted over time and should, in the long term, reduce the number of vehicles in the national fleet, if not the number of vehicles on the road at any one time. The ability to pay for transportation on an as-needed basis could substantially reduce expenses for many people. Moreover, if fewer vehicles are parked, then parking lots can be converted to some other useful purpose, and the 30% of land devoted to parking in some urban areas could be greatly reduced (Manville and Shoup 2005).

Many of these arguments are laid out in an industry report by KPMG and CAR (Silberg and Wallace 2012). The tone of the report is very bullish on the adoption of autonomous

vehicles and stresses the synergy of automation and connected vehicle technology (the addition of wireless networking to vehicles). It is of course impossible to know when the technology will come to fruition and how quickly it will be adopted by consumers. Roy Amara, researcher and scientist, said famously, “We tend to overestimate the effect of a technology in the short term and underestimate the effect in the long run.” The implications for autonomous vehicles are exciting, even if their path to deployment doesn’t go exactly as predicted.

Chapter 2 A Brief History of Autonomous Vehicles

2.1 Early Decades

The idea of autonomous vehicles has been with us almost as long as the automobile. Among other efforts, a full-scale test of an automated highway was conducted in 1958 near the University of Nebraska on a 400 foot strip of public highway by RCA Labs and the State of Nebraska (see Figure 2.1). The technology depended on detector circuits that were installed in the roadway which could detect the speed of the car and send it guidance signals.

Work on autonomous vehicle projects continued, leading up to successful demonstrations by Carnegie Mellon University in the late 1980s (Kanade, Thorpe, and Whittaker 1986) and the Prometheus Project by EUREKA in Europe (Luettel, Himmelsbach, and Wuensche 2012). Something special happened in the 1990s, though, that sparked research into autonomous vehicles on a larger scale. Increased government funding spurred research and brought academics and industry together. Computing hardware continued to increase in power and shrink in size. However, it may also have been due to witnessing a successful demonstration of the technology. As with the breaking of the four minute mile, the threshold had been crossed, and a host of other competitors would enter the field.

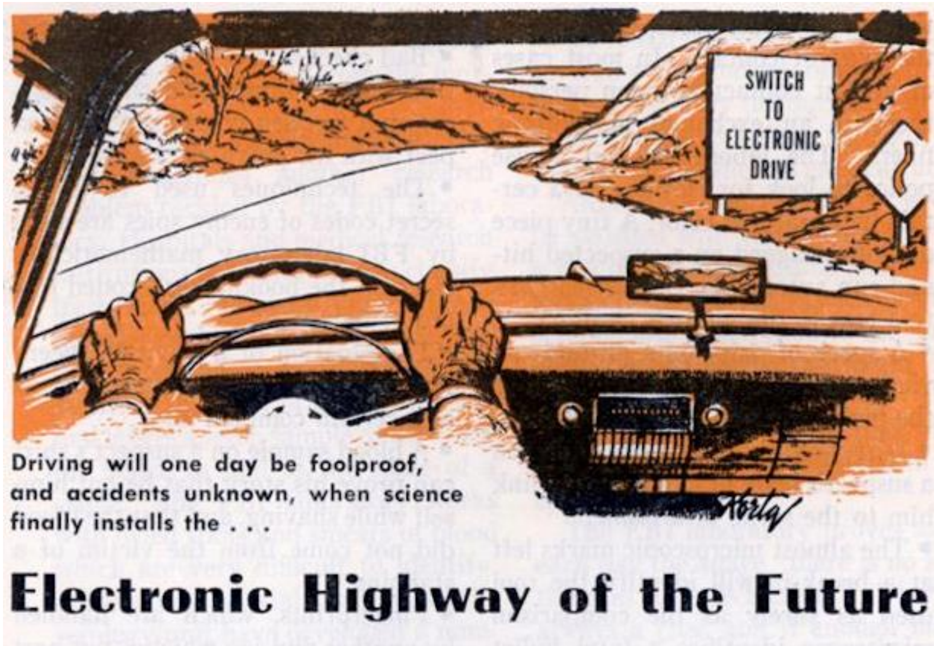


Figure 2.1 An early experiment on automatic highways was conducted by RCA and the state of Nebraska on a 400 foot strip of public highway just outside Lincoln ("Electronic Highway of the Future - Science Digest" [Apr, 1958] 2013)

2.2 <u>National Automated Highway System Research Program</u>

The Intermodal Surface Transportation Efficiency Act (ISTEA) transportation authorization bill, passed in 1991, instructed the USDOT to demonstrate an automated vehicle and highway system by 1997. This inspired the FHWA to create the National Automated Highway System Consortium (NAHSC). Partners included General Motors, Caltrans, Bechtel, Parsons Brinkerhoff, Lockheed Martin, Hughes, Delco Electronics, California PATH, and Carnegie Mellon University (TRB 1998).

Despite the program's focus on automated *highways*, there were advocates even then of a vehicle-based, or free agent, approach (C. Urmson et al. 2008). About three years into the program, DOT commissioned a study on the appropriateness and effectiveness of the NAHSC mission. It was becoming apparent that the complete specification of an autonomous highway

system was too difficult to solve at that time. Additionally, the infrastructure demands of the automated highway approach would have carried an immense cost. As a result, the decision was made to shift the focus to shorter-term research goals that could be commercialized at an earlier date. Nevertheless, a system was developed, and a demonstration was held in 1997 of an automated highway system as well as a free agent system.

2.3 Intelligent Vehicle Initiative

The Intelligent Vehicle Initiative (IVI) began in 1997 and received authorization as part of the 1998 Transportation Equity Act for the 21st Century (Hartman and Strasser 2005). The stated purpose of the IVI was to accelerate the development and commercialization of vehicle-based and infrastructure-cooperative driver assistance systems. It would do this through the two-pronged strategy of reducing driver distraction and accelerating deployment of crash avoidance systems. This approach to vehicle safety was a departure from previous efforts in that it was focused on crash prevention rather than crash mitigation, and on vehicle-based rather than highway-based solutions.

Several systems were developed and deployed in field-operational tests (FOT). The systems included forward collision warning (FCW), adaptive cruise control (ACC), lane departure warning (LDW), lane change assist (LCA), intersection movement assist (IMA), and vehicle stability systems for commercial vehicles. Due to the long list of public and private partners involved in IVI, commercial versions of these systems were indeed introduced during those years, and their market penetration has been increasing ever since. Figure 2.2 shows a comprehensive system developed for an Integrated Vehicle-Based Safety System (IVBSS) FOT that was conducted by the University of Michigan Transportation Institute (UMTRI).

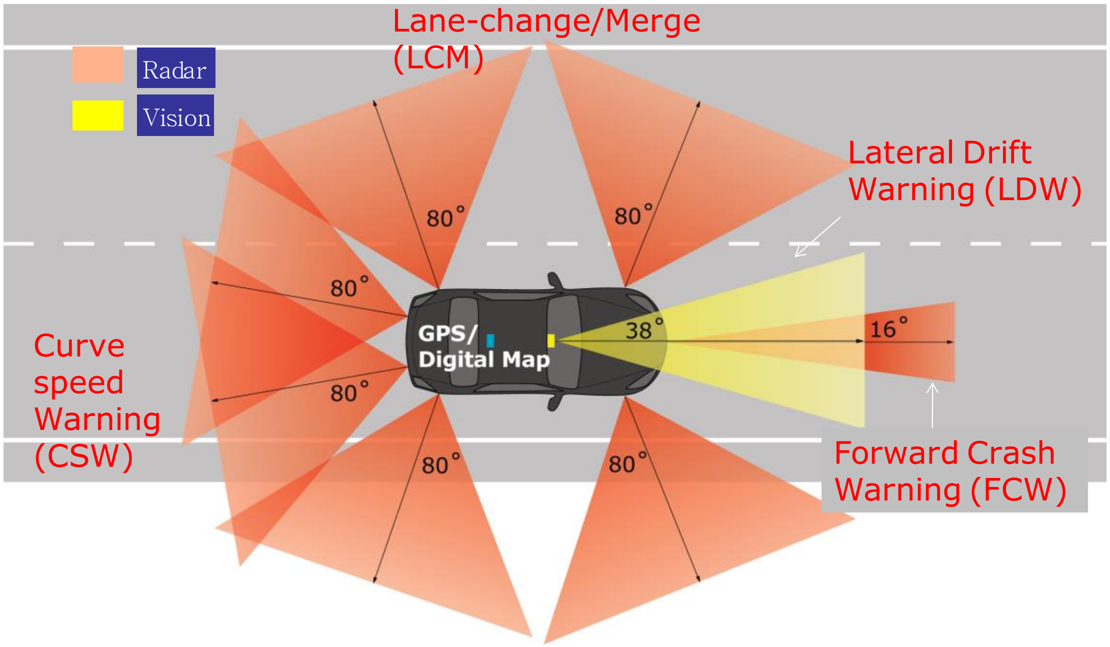


Figure 2.2 Multiple ADAS systems. Image from IVBSS materials, courtesy of University of Michigan Transportation Institute

2.4 <u>DARPA Grand Challenges</u>

The Defense Advanced Research Projects Agency (DARPA) held three grand challenges in the first decade of this century focused on the development of feasible autonomous vehicles. The first was an off-road challenge to successfully navigate a 132 mile course through the Mojave Desert in no more than 10 hours. It was held in 2004; no vehicle completed more than five percent of the course. The challenge was repeated in 2005; and out of 195 entries, five vehicles finished the course, four in the allotted time. The winner was Stanley, the entry from Stanford University (Montemerlo et al. 2006; Thrun et al. 2007).

The third challenge was to drive autonomously through a 97 km course in an urban environment, following the rules of the road, and interacting with other vehicles. A total of 89 teams registered for this event. After a series of preliminary steps, DARPA narrowed the field to 36 teams that were invited to participate in the National Qualification Event. Finally, eleven

teams participated in the Urban Challenge Final Event, and the winner was the entry from Carnegie Mellon University, named Boss (Chris Urmson et al. 2008). Pictures from the off-road and urban challenges are shown in Figure 2.3.

(a) (b)

Figure 2.3 DARPA Grand Challenge (a) and Urban Grand Challenge (b) courses (image credit: Wikipedia 2013)

The DARPA Grand Challenges captured the attention of the press and the imagination of many current and future roboticists. The techniques used in the vehicles encompass all the basic elements of today's autonomous vehicles, and the Google Car is descended from Stanley. The main difference, however, was that DARPA was interested in *unmanned* ground vehicles (UGV), while the Google Car and its peers are being developed principally as manned vehicles. Military interest in unmanned ground and aerial vehicles continues unabated; they are featured prominently in joint Future Combat Systems (FCS) vision.

2.5 Connected Vehicles

The IVI recommended that research continue into cooperative vehicle technologies, and one of its trailing projects was the cooperative intersection collision avoidance system (CICAS). The Vehicle Infrastructure Integration (VII) program was established in 2005, and a consortium was assembled among three car manufacturers to develop and test a proof-of-concept system based on a wireless communication system based on the Dedicated Short Range Communications (DSRC) protocol. Soon after, a cooperative agreement was signed between the VII consortium (VIIC) and the USDOT FHWA to work together on specifications, design, fabrication, test, and evaluation of the VII architecture (Andrews and Cops 2009; Kandarpa et al. 2009). The FCC allocated 75 MHz at 5.9 GHz for DSRC for the primary purpose of improving transportation safety.

Figure 2.4 Connected vehicles concept (image credit: NHTSA 2013)

Later in the decade, the DOT established a new program, called IntelliDrive, which encompassed all the activities of the VIIC. Eventually, the name changed again to become the Connected Vehicles program (NHTSA 2011). The threefold objectives of the Connected Vehicles program are to use vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication to significantly impact safety, mobility, and sustainability in the transportation system.

The V2V concept can be seen in Figure 2.4. Several scenarios were identified to motivate the foundational safety application based on crash causation studies. The safety scenarios are listed in Table 2.1. A safety pilot of the technology has been ongoing in Ann Arbor, Michigan, and conducted by UMTRI; and a decision from DOT is expected soon about their future intentions for the technology.

Table 2.1 Connected vehicles safety scenarios

Application	Description
Emergency Stop Lamp Warning	Host vehicle broadcasts an emergency braking event to surrounding vehicles
Forward Collision Warning	Warns the host vehicle of an impending collision in the same lane – not line-of-sight restricted
Intersection Movement Assist	Warns the host vehicle not to enter an intersection if a side collision is likely
Blind Spot and Lane Change Warning	Warns the host vehicle if their blind spot is occupied when a turn signal is activated
Do Not Pass Warning	Warns the host vehicle not to pass a slow-moving vehicle if there is an oncoming vehicle in the passing lane
Control Loss Warning	Host vehicle broadcasts a control loss event to surrounding vehicles

2.6 NHTSA Automation Program

The emergence of the Google Car around 2010 had a disruptive effect in the industry even though the technology will not be commercially available for several years. Since then, several car manufacturers have developed their own autonomous vehicle programs and demonstrated working prototypes. Additionally, the use of autonomous vehicles was legalized in Nevada, California, and Florida, with more likely to come. These events, among others, caused NHTSA to begin a program of research into automated vehicles and create a new division for that purpose in 2012. After only a year or so, and perhaps because of the fast pace of activity, NHTSA released a preliminary policy statement concerning automated vehicle (NHTSA 2013b), the bottom line of which was to recommend to states that they *not* allow the legal operation of automated vehicles except for research and testing at this time.

Table 2.2. NHTSA levels of vehicle automation (NHTSA 2013b)

Level 0	No Automation	Driver in complete and sole control. Includes sensing-only systems like FCW, LDW.
Level 1	Function-specific Automation	Driver has overall control. One or more specific control functions automated (ACC, ESC).
Level 2	Combined Function Automation	At least two primary control functions are automated. Driver responsible for monitoring safe operation and is available for control on short notice.
Level 3	Limited Self-Driving Automation	Driver cedes full control to automation under certain conditions. Driver is available for occasional control, but does not have to constantly monitor safe operation.
Level 4	Full Self-Driving Automation	Driver supplies destination or navigation support, but is not expected to be available for control at any time during the trip.

That policy statement summarized the taxonomy that NHSA has adopted for the levels of automation in vehicles, summarized in Table 2.2. Systems of levels zero and one have existed for several years at this point; level two systems are soon to be introduced in high-end vehicles

that will allow the driver to give over both pedal and steering control to the vehicle. The Google Car is at level three in its current incarnation. Current level four systems include some forms of personal rapid transit and unmanned ground vehicles used by the military.

In the meanwhile, automation programs are underway around the world with Europe and Asia being slightly ahead of the USA in terms of adoption of the technology. Both Nissan and Mercedes have claimed that they will sell autonomous vehicles by 2020 (Vijayenthiran 2013, Howard 2013), and Volvo has plans to start testing autonomous vehicles in traffic starting in 2017 in Sweden (Laursen 2013). Google has not set a date for commercializing its technology, but is optimistic as well about the timeline.

Chapter 3 Towards Autonomous Vehicles

3.1 A Bottom up Approach: Advanced Driver Assistance Systems

The IVI brought with it a new focus on accelerating the development of systems that could be commercialized on a short time horizon. Ever since that time, vehicle manufacturers have been adding new systems to their portfolio, and these systems have gradually evolved from passive (warnings) to active (interventions). Collectively, they have been grouped under the title of Advanced Driver Assistance Systems (ADAS).

As more and more ADAS devices enter the market, they begin to cover more regions of vehicle operation, and the sensors cover more of the space surrounding the vehicle. Additionally, the integration of multiple systems began to make use of shared sensor suites and common computing resources. In other words, over time, ADAS-equipped vehicles begin to look more like autonomous vehicles. Table 3.1 summarizes the results of a recent ADAS survey. ACC stands for adaptive cruise control, and LDW is short for lane departure warning.

Table 3.1 A 2011 review of commercial ADAS systems compares manufacturers, model year, and sensor type for three types of systems (Shaout, Colella, and Awad 2011).

	ACC		Pre-Crash		LDW	
	Sensor	**Year**	**Sensor**	**Year**	**Sensor**	**Year**
Audi			Radar/Video	2011	Camera	2007
BMW					Camera	2007
Chrysler	Laser	2006				
Ford	Radar	2009	Radar	2009	Camera	2010
GM	Radar	2004			Camera	2008
Honda			Radar	2003	Camera	2003
Kia					Camera	2010
Jaguar	Radar	1999				
Lexus	Laser	2001				
Mercedes	Radar	2001	Radar	2002	Camera	2009
Nissan					Camera	2001
Saab	Radar	2002				
Toyota	Laser	1998	Radar	2003	Camera	2002
Volkswagen			Radar/Video	2011		
Volvo	Radar	2002	Radar/Video	2007		

Table 3.2 A list of advanced driver assistance systems

Abb.	System	Abb.	System
ACC	Adaptive Cruise Control	**HC**	Highway Chauffeur
AEBS	Advanced Emergency Braking	**HP**	Highway Pilot
AL	Adaptive Lighting	LDW	Lane Departure Warning
BSD	Blind Spot Detection	LKA	Lane Keeping Assist
CZA	Construction Zone Assist	**PA**	Parking Assistant
DD	Drowsiness Detection	**PP**	Parking Pilot
EBA	Emergency Brake Assist	**PM**	Pedal Misapplication
ESA	Emergency Steer Assist	RCTA	Rear Cross Traffic Alert
ESC	Electronic Stability Control	**TSR**	Traffic Sign Recognition
FCW	Forward Collision Warning	**TJA**	Traffic Jam Assistant

Unfortunately, the Shaout survey is significantly out of date just two years later. The deployment of new ADAS systems continues to explode; the introduction of the first systems with automation level two is happening now. A more comprehensive list of ADAS systems is offered in Table 3.2. From a general perspective, automation systems may do two broad kinds of activities: perceive their environment, and act on their environment. Figure 3.1 plots action versus perception and places the ADAS systems from Table 3.2 approximately where they belong relative to one another, and relative to a human driver. The figure also layers on the NHTSA levels of automation. Given the extensive sensor ranges and fields of view, it is certainly the case that some systems have greater perception ability than a human.

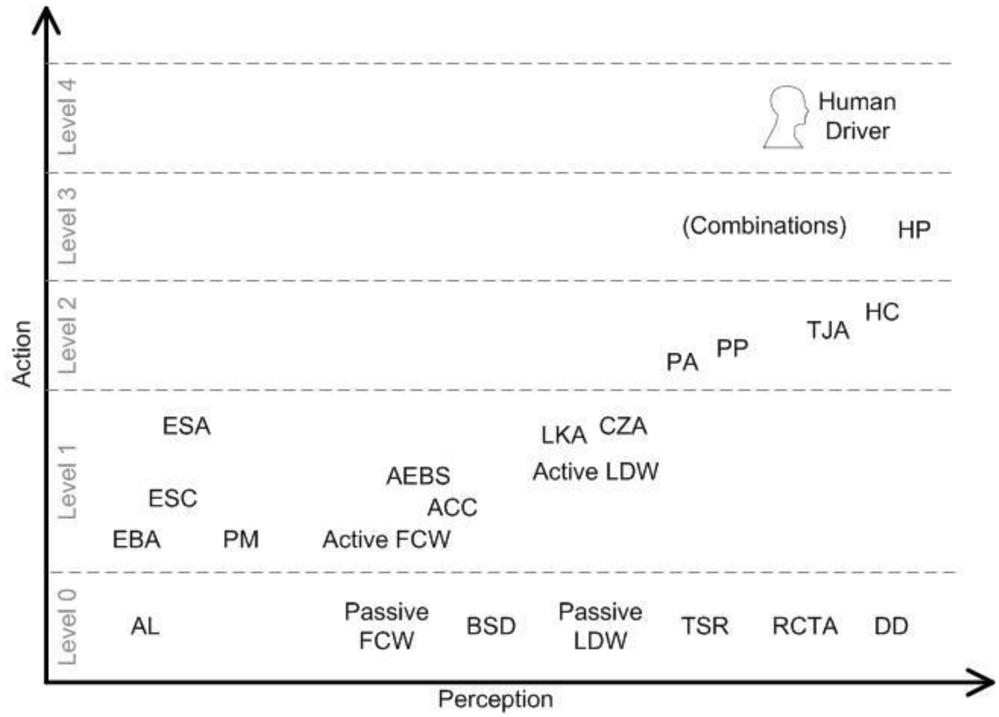


Figure 3.1 Various ADAS systems mapped onto levels of automation and degrees of agency

The figure makes it very clear that the level of automation is purely determined by an automation function's *action* authority, and not its perception capability. This is a boon to manufacturers who have been able to continuously improve their sensor suites and perception algorithms without jumping up the automation scale and taking the risk of acting improperly. The other strategy that manufacturers use to avoid liability concerns is to market the ADAS as a convenience system, like adaptive cruise control (ACC).

The ADAS approach lends itself to evolutionary and iterative progression towards fully autonomous vehicles, but it also begs the question: will this bottom-up approach converge at level-four automation? The answer to this question is not at all obvious. It has been clear for 20 years that the main barriers are not only technical but socioeconomic in nature. It seems that Google's entry into the vehicle automation space has had a disruptive effect on the industry that may push through some of these barriers. Since around 2010, significant progress has been

made on addressing the legal issues surrounding automation, on advancing the deployment of more ADAS devices, and on aiming for the goal of a fully autonomous vehicle.

3.2 A Top-Down Approach: Starting at Full Automation

It would be a mistake to assume that there are not level four autonomous vehicles currently in use; indeed, there have been examples of these for decades. They take the form of automated guideway transit (AGT) vehicles, which may be classified into very small vehicles for personal rapid transit (PRT), and larger vehicles for group rapid transit (GRT). Other variations of the idea have different names, such as cybercars, but all such vehicles share a lack of operator and of driver controls. We will review some work that uses smaller vehicles comparable in size and application to passenger vehicles.

Personal rapid transit networks were a popular area of research in the 1970s and are regaining some of their luster, especially in Europe (MacKinnon 1975; Parent and Daviet 1996; Anderson 2000; H. Muir et al. 2009). The general idea involves cars that run on fixed guideways and stop at stations for passengers. This sounds like a train, but the PRT design works more like an elevator that is called when needed. Station designs can be quite complicated, but most designs made them offline, which means that cars could stop for passengers without interrupting the main flow of cars on the guideway. The station capacity is related to how many berths are supplied for embarking and alighting.

The oldest commercially operating PRT is in Morgantown, West Virginia, at the University of West Virginia. It has a capacity of 240 vehicles per hour, though its theoretical capacity is twice that if the headway is halved from 15 to 7.5 seconds. A newer PRT system was installed at Heathrow airport in London to serve passenger and staff car parks (Lowson 2005).

The ULTra PRT system (see Figure 3.2), as it is known, promises a reduction of 60% in trip times and of 40% in operating costs over a legacy bus system.

Figure 3.2 ULTra PRT vehicle on a test track

While many PRT networks have been proposed over the years, very few have been completed and deployed. Critics of the PRT approach have pointed out several potential reasons for their glacial pace of adoption. Sulkin described three types of obstacles on PRT systems (Sulkin 1999): (1) required station size and complexity, (2) the limitations of station interval, and (3) problems of scaling to large fleets.

An assumption of offline stations is made so that capacity demands can be met. That requires all deceleration, docking, and accelerations to be made on guideways separate from the main one. The physics of this, combined with the space limitations of providing enough berths per station, account for the first two concerns. The third concern comes from an analysis of mean time between failures (MTBF) and mean time to restore (MTTR) as the fleet size grows that concluded that large fleets would necessarily suffer from reductions in the availability of

functioning vehicles. More recently, Cottrell (Cottrell 2005) noted six unresolved problems with PRT designs:

1. Technical problems of reliability and safety
2. Lack of government investment
3. Lack of planning integration into urban designs
4. Bad publicity
5. High perceived risk
6. Competing interests from traditional transit modes

Disappointingly, a new PRT system designed for Masdar City (Mueller and Sgouridis 2011), a zero-emission model city in Abu Dhabi, that was ostensibly well planned and integrated from the start was cut at the pilot stage as a cost-saving measure (Carlisle 2010).

Renewed interest in PRT systems has resulted in a great deal of ongoing work in Europe (Adriano Alessandrini, Parent, and Holguin 2008; A. Alessandrini, Parent, and Zvirin 2009; H. Muir et al. 2009), including two major projects: CityMobil (2006-2011) and CityMobil2 (2012-2017). CityMobil had three major demonstrations, including the Heathrow PRT system, a cybercars project in Rome, and an advanced bus rapid transit (ABRT) project in Valencia. The CityMobil2 program will include 13 cities and six different manufacturers.

The EU programs are expanding beyond traditional PRT designs to dual-use concepts (guideway or road operation), cybercars, and tiny cars. Cybercars are fully autonomous road vehicles that originated in Europe and now come in many forms and sizes for personal or group use. While they don’t use guideways, they do typically operate at low speed out of safety concerns.

Despite their slow pace of adoption, true autonomous vehicles in several forms are finally being developed. This top-down methodology is an important contribution to the goal of deploying vehicles that can freely navigate on U.S. roads and highways.

Chapter 4 Challenges of Autonomous Vehicles

4.1 Technical

There are several fundamental questions that an autonomous vehicle needs to answer about its environment. Where am I in the world? Where is the road? Where are static and moving objects? How do I get from point A to point B? These questions that are normally the purview of the driver are incredibly challenging to the modern automation system, even though the first examples of autonomous vehicles appeared on tracks in the 1970s and on the road in the 1980s. All of these questions are related to technical terms for topics of research in robotics and autonomous vehicles. Loosely, we may classify them as in Table 4.1.

Table 4.1 Research topics in autonomous vehicles

Question	Research Area
Where am I?	Localization
Where is the road?	Localization, Digital Mapping
Where are static and moving objects?	Object Detection and Classification
How do I get from point A to point B?	Digital Mapping, Path Planning, Decision Making

4.1.1 Sensors

Vehicles have a host of sensors that have been used to estimate vehicle motion and location for many years. Wheel speed sensors, accelerometers, gyroscopes, potentiometers, and other basic sensors are used in many control functions (like cruise control) and began to be integrated into more advanced control systems starting with anti-lock brakes and leading into traction control and electronic stability control.

Odometry is the practice of using data from sensors like the ones listed above to obtain estimates for vehicle speed and position. Since this process requires integrating the sensor

signals, it is subject to the accumulation of drift errors. Drift results from small errors due to calibration or misalignment to build up over time as signals are integrated to position with the constant of integration not precisely accounted for. Additionally, the use of wheel speed sensors for odometry is susceptible to errors caused by tire slip against the ground.

Geospatial sensors have been used on cars since the 1980s in navigation systems and have since also been integrated into portable navigation devices, smartphones, and many other devices. Since the beginning of the century, the accuracy of GPS has improved due to the elimination of “Selective Availability,” which intentionally degraded the signal, as well as the deployment of newer GPS satellites. Nevertheless, GPS can suffer from signal dropouts and multichannel interference in areas with tall buildings, i.e., urban canyons (Cui and Ge 2003).

Radar has enjoyed a great deal of success and growth in automotive sensor applications, like parking aid, collision warning, blind spot warning, and emergency braking systems since the 1990s (Klotz and Rohling 2000; Schneider 2005). Long range radar (LRR) can sense objects at up to 150 meters and operates at a frequency of 77 GHz. This type of radar is used in long range sensing applications such as ACC. Mercedes first introduced 77 GHz radar in their S class vehicle in 1999. Short range radar (SRR) has a range of up to 20 meters and operates at 24 GHz with a resolution of just centimeters. Short range radar is appropriate for collision warning systems, parking aid systems, blind spot warning systems, etc. While SRR is often implemented with a single antenna design, and thus cannot detect angle, LRR systems more often incorporate digital beamforming technology and can discern angle with a resolution of around two degrees. An LRR sensor adds several hundred dollars to the cost of car (around $1000 in 2011 [Fleming 2012]).

The use of sound for range-finding has been explored using ultrasonic sensors for some time (Parrilla, Anaya, and Fritsch 1991). An ultrasonic sensor for automotive applications was described in 2001 (Carullo and Parvis 2001). This type of sensor is attractive for its low cost (about one dollar per sensor); however, the sensor's signal can be degraded by surrounding noise. Carullo and Parvis tested the sensor as a way to measure distance to the ground and found good accuracy, but increasing uncertainty, in the measurement as speeds increased. This application of the ultrasonic sensor is one that can add accuracy and robustness to odometry estimates with other sensors since each sensor's position in the world can be accurately updated over time as the suspension displacements change.

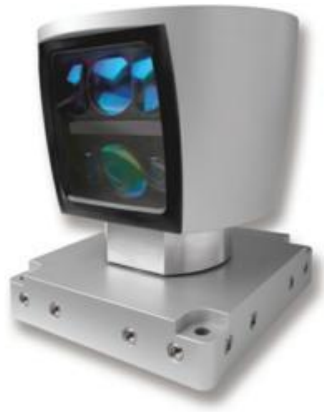
The introduction of cameras into the vehicle really started as a way to provide novel displays to the driver for greater effective field-of-view, as with the back-up camera. However, cameras have been used as a primary sensor in robotics for decades and have been introduced into production vehicles in lane departure warning systems. Cameras are considered an essential part of autonomous vehicle technology because vision can deliver spatial and color information that other sensors cannot. For example, no sensor previously mentioned is capable of detecting a painted line on a road. Cameras are also very useful in algorithms that detect and classify objects as pedestrians, cars, signs, etc. (Ess et al. 2010; Guo, Mita, and McAllester 2010; García-Garrido et al. 2012; Luettel, Himmelsbach, and Wuensche 2012). The research vehicle Navlab at Carnegie Mellon University used cameras and a lateral position handling system called RALPH to driver over 3000 miles on highways with automated lane handling up to 96% of the time (Pomerleau 1995). In 2002, Dickmanns summarized the state of the art of camera sensors, noting that the bottleneck was the amount of data that needs to be processed from an image (Dickmanns 2002). He figured that Moore's law would control the rate of advances with vision

sensing and estimated that there would be enough computing power to adequately implement real-time image processing by around 2010; his prediction has been fairly accurate. Cameras can add several hundred dollars to the cost of a vehicle (Carrasco, de la Escalera, and Armingol 2012).

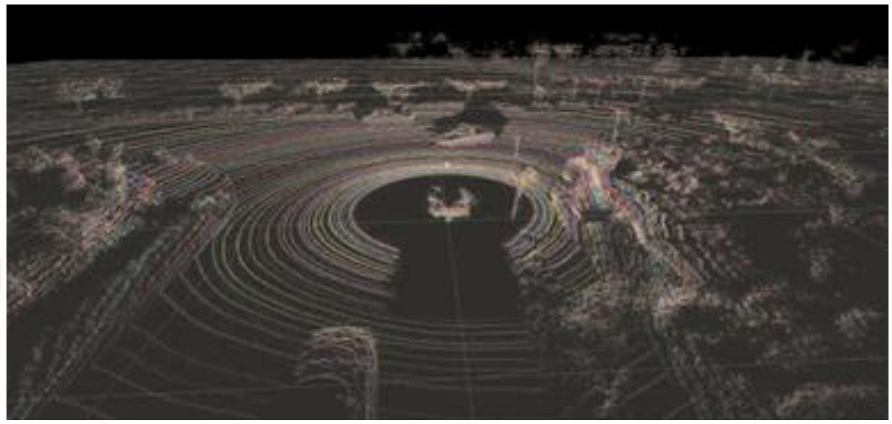
Autonomous vehicles have commonly obtained their acceleration and rotation measurements from devices called inertial measurement units (IMU) that surpass the capabilities of accelerometers and yaw rate sensors for ESC systems. Unfortunately, IMUs for research vehicles have been quite expensive devices (Wang, Thorpe, and Thrun 2003); however, there are IMUs available for under $1000. IMU data is commonly fused with GPS data because their strengths and weaknesses are very complementary. While IMU measurements drift, GPS measurements are absolute; and while GPS measurements may drop out or experience jumps, IMU data is continuous (Sukkarieh, Nebot, and Durrant-Whyte 1999; Jesse Levinson, Montemerlo, and Thrun 2007; Milanés et al. 2012).

The sensor that stands out on most research-grade autonomous vehicles is the spinning LIDAR sensor mounted on top of the roof. LIDAR uses light pulses that reflect off objects and are reflected back to the sensor. The round-trip time of the light pulse is used to deduce the range. A rotating mirror is used to scan the environment with the laser, and the scanning range may vary from narrow to full surround. As with IMUs, research-grade devices are quite expensive. The Velodyne sensor used on the first Google Car reportedly cost around $70,000, making up almost half the cost of the vehicle. Production LIDARs are smaller and make compromises in the angular scanning range and in how many laser scanning lines (layers) there are. The Velodyne sensor pictured in Figure 4.1 uses 32 scanning lines, while Ibeo makes a

four-layer LIDAR for automotive applications. Nevertheless, LIDAR sensors remain the most expensive of the advanced sensing technologies.



(a)



(b)

Figure 4.1 Velodyne LIDAR sensor (a), and visualization of environment (b) (Velodyne 2007)

If vehicles are equipped with wireless network technology, such as DSRC transceivers, then the vehicle may receive information about surrounding vehicles as well as from the infrastructure. This type of sensor has its own intrinsic advantages and disadvantages. The main benefit is that wireless connectivity is not limited by line of sight; and vehicle-to-vehicle (V2V) communication can take place even if the driver cannot see the target vehicle. This type of sensor makes the idea of closely spaced platoons much more feasible. The disadvantages of these types of sensors are the latency (~100 ms), the bandwidth requirements, and security/privacy concerns. The DSRC technology communicates at 5.9 GHz and is considered fast enough to be used in safety applications.

Finally, digital maps may be thought of as a sensor, a very long-range sensor. Like DSRC, line of sight is not a limitation of maps, nor is weather or other ambient conditions. Maps are essential components of on-road autonomous vehicles and allow navigation planning

activities to occur. Digital maps allow the computationally intensive task of mapping one's environment to be separated in time and cost from an autonomous vehicle that simply wishes to access the map. On the other hand, digital maps are relatively static and grow dated over time. Moreover, they do not communicate information about moving objects or temporary situations such as construction zones without additional input from a traffic service.

4.1.2 Localization

Today's autonomous vehicles rely on a combination of advanced sensors to provide a complete picture of the environment. The challenge of processing and synthesizing all this data into a unified picture is one of the challenging aspects of multiple sensor integration. Data fusion, as this problem is known, is a cornerstone of multi-sensor localization systems. The problem is that each sensor has its own unique kind of noise, its own calibration settings, and its own distinctive fault modes. An effective data fusion strategy checks for consistency, recognizing when one sensor is in an error state (Sukkarieh, Nebot, and Durrant-Whyte 1999). By using techniques that are able to deal with noisy and uncertain measurements, effective localization is possible, and getting better all the time (see sidebar –*Kalman Filters: The workhorse of data fusionKalman Filters: The workhorse of data fusion*).

<u>*Kalman Filters: The workhorse of data fusion*</u>

Kalman filters are one of the main techniques for fusing data from separate sources (Kalman 1960; Kalman and Bucy 1961). *They represents the sensor noise with a normal distribution (white noise). It also knows about the system being measured, as a linear model must be specified. The filter is then able to come up with an optimal estimate of the true measurement, given the noise sensor data. If linearity cannot be satisfied, then more complex variants, the extended Kalman filter (EKF) and unscented Kalman filter (UKF), may be used instead* (Hudas et al. 2004; Bento et al. 2005; Najjar and Bonnifait 2005; Luettel, Himmelsbach, and Wuensche 2012).

These filters fall into a broader category of Bayesian techniques for probabilistic reasoning about uncertain systems, and much progress has been made along these lines in the last 20 years (Roumeliotis and Bekey 2000; J. Levinson and Thrun 2010). *Much of the success of the DARPA challenges and Google Car can be attributed to the ability of probabilistic algorithms to process huge amounts of data from disparate sources and synthesize it into a coherent whole that can be utilized by a control system or decision-making algorithm.*

4.1.2.1 Mapping

One of the main evolutions from early off-road research to modern autonomous vehicle development is the use of digital maps to chart a course rather than planning a path from scratch in real time. Unfortunately, it is not always possible to have a map of one's environment. Consider unstructured pathways around buildings and in parking lots, construction zones and detours, accident scenes, flooded streets, and the like. It is still necessary to augment digital maps with additional generated maps to fill in the gaps. This problem has been widely studied in the context of robotics and autonomous vehicles and is referred to as the simultaneous localization and mapping (SLAM) problem.

It may seem odd at first glance that it’s not referred to as just a mapping problem, but upon some reflection, it’s not hard to see that mapping cannot be separated from localization without ending up with a distorted map in the end. Thus the quandary of SLAM is that of the chicken and the egg. How does one localize without a map; and how does one make a map without knowledge of location? Fortunately, it is possible by incrementally building up a set of landmarks and mapping new points in relation to them (Leonard and Durrant-Whyte 1991; Dissanayake et al. 2001; Wang, Thorpe, and Thrun 2003; Durrant-Whyte and Bailey 2006; Bailey and Durrant-Whyte 2006).

Apart from using a SLAM algorithm to complete a vehicle’s picture of the environment, one must solve the correspondence problem when accessing digital maps. That is, how does one find one’s exact position on a digital map? This is a problem that is tackled behind the scenes in all navigation systems, and sometimes imperfectly when you see your car’s marker jump sporadically from one road to another. When available, landmarks that correspond between the map and a SLAM procedure may be used as a fixed point. Cameras can detect lateral lane placement or detect and classify other types of landmarks (Yang and Tsai 1999; Li, Zheng, and Cheng 2004; Byun et al. 2012), and LIDAR can be used to detect curb locations, both of which should have some correspondence to the digital map (Jesse Levinson, Montemerlo, and Thrun 2007). In between landmarks, odometry information can be used to update the position in the map (Najjar and Bonnifait 2005; Fouque, Bonnifait, and Betaille 2008). This is also sometimes called dead reckoning.

There are many ways to combine sensors to solve the localization problem. The position and motion of the vehicle (i.e., ego-location) is usually obtained using GPS, IMU, and digital

maps. The map correspondence problem can be solved using cameras or LIDAR, along with odometry. Simultaneous localization and mapping can be done using vision and/or LIDAR.

4.1.3 Object Detection

It is not enough for an autonomous vehicle to know where it is. It must also know where other obstacles, both moving and stationary, are located and where they're headed. The detection and tracking of moving objects was addressed by the Carnegie Mellon team on their Navlab testbed using laser scanners and odometry (Wang, Thorpe, and Thrun 2003). The SLAM and DATMO (Detection and Tracking of Moving Objects) problems are interrelated in that everything is picked up by the sensors, and moving objects need to be classified as such and removed from the map. Recent work on object detection in busy urban environments using cameras demonstrates the advances that have been made in this area (Ess et al. 2010; Guo, Mita, and McAllester 2010).

As in localization, probabilistic methods are used to detect and track moving objects. Data association is a problem in which the algorithm defines objects (cars, pedestrians, etc.), and then tries to associate a sensor image with its appropriate object. This can be complicated as objects pass in front of one another or leave and reenter the sensor's range. Also, false sensor readings may inadvertently be classified as an object, adding additional noise to the process. The CMU team achieved a robust algorithm that worked over long stretches of time in 2003, and the real-time algorithms have only improved over time as computer power has increased.

4.1.4 Path Planning

We are familiar with the type of path planning that navigation systems do to generate the shortest routes to our desired destination. Road segments between intersections/on-ramps/exits are termed links, and links are joined together to form a tree of possible routes. The pre-eminent

method for finding the shortest route in this setting is still the A* algorithm (Hart, Nilsson, and Raphael 1968; Hart, Nilsson, and Raphael 1972) and variants thereof, and we know from experience with our navigation systems that it works well (most of the time).

The path planning problem for autonomous vehicles is more complicated than the basic navigation problem, however. Autonomous vehicles must also plan detailed and smooth paths, such as for lane changes and turns, and they must be able to plan paths in semi-structured and unstructured environments. Finally, their plans must be able to take dynamic obstacles into account. A* has been generalized to address the unstructured setting in such a way as to generate smooth trajectories (Dolgov et al. 2010). It is important to understand that vehicle paths must be constrained by their steering systems, so arbitrary paths may not be feasible (Byun et al. 2012). Self-parking cars have recently been demonstrated and show that this kind of path planning can be quite useful and is ready for commercialization.

4.1.5 Decision making

Control systems for complex machines often take on a hierarchical structure. Such a structure for autonomous vehicles would have the low-level control of the steering and pedals to regulate speed and lane placement at the bottom. Mid-level controllers might handle a whole host of specific situations, such as imminent collisions, lane changes, ACC, and the like. Finally, high-level controllers would contain the “brains” of the vehicle, that part of the system that is responsible for behaviors and decision making. Even cutting-edge autonomous vehicle technology cannot yet replace the human at this level.

The highest level of control is what we usually equate with Artificial Intelligence (AI); but, really, AI has permeated the technologies we have discussed in this report. Progress is being made to make autonomous behaviors more and more complex. Overtaking another vehicle is a

rather complicated maneuver, requiring several decisions to be made, and has been successfully automated (Milanés et al. 2012). A hierarchical automation scheme was used in the Cognitive Automobile AnnieWAY (Stiller and Ziegler 2012). Such schemes must be able to take data from the low-level systems and abstract it into symbolic knowledge for consumption by decision-making systems.

Perhaps even greater feats of reasoning are required to enable the human driver and the automation able to cooperate and function as an effective team, and this is a scenario that will be encountered on US roads before autonomous vehicles are deployed in large numbers. Some efforts to employ cognitive modeling in automation are trying to make the vehicle "think" more like a human (Hoc 2001; Heide and Henning 2006; Baumann and Krems 2007; S.-H. Kim, Kaber, and Perry 2007). To the extent that these efforts succeed, we may see autonomous vehicles employ human-like reasoning and decision making.

4.2 Human Factors

The human factors issues surrounding driving have gradually increased in importance as well as in attention paid to them for several decades. Pedal misapplications in the 1980s resulted in the inclusion of a brake-shift interlock system in all cars. Guidelines and standards have evolved for many facets of car interior design as relates to the placement and operation of common controls, both primary (e.g., steering) and secondary (e.g., radio). However, as the pace of technology quickens, the human factors of vehicle and interface design have become more crucial to preserving a safe driving environment. The incorporation of new warning systems into vehicles requires thought as to how best to communicate those warnings to the driver to prevent confusion or startle. The introduction of new external technology into the vehicle (phones, navigation aids) raises concerns about distraction. Finally, the move towards vehicle automation

requires a great deal of thought about how to best support the driver while avoiding known pitfalls like complacency, distrust, and out-of-the-loop performance problems. This section summarizes some of what we know about the human factors of automation in vehicles.

It is worthwhile to review our motivation for considering semi-autonomous operation in this report. Primarily, it is due to the realization that vehicles will undergo a gradual path to full automation, first using the other automation levels 1-3 (see Table 2.2). As a result, drivers' mental models of the autonomous vehicle will be heavily informed by their previous experiences with automation in the car. However, even if we were to delay the introduction of automation until level 4 was available in their cars, we would run the risk of alienating drivers by displacing their expertise and putting them into a passive and helpless position (Sheridan 1980; Sheridan, Vámos, and Aida 1983; Muir 1987). Perhaps the best way to combat this, from a human factors perspective, is to allow the driver to experiment with and explore the various levels of automation so that understanding and trust is developed, and to find ways to maintain the driver as an "expert" in the vehicle in some capacity.

4.2.1 Out-of-Loop Performance Loss

One known problem with high levels of automation is that the human operator is delegated to a passive, rather than active, role. It turns out that humans are not very good at passively monitoring automated systems and become complacent over time (Endsley and Kiris 1995; Sheridan and Parasuraman 2005). Moreover, when humans are out of the loop (OOTL) like this, they suffer performance penalties when they are required to take back manual control. One common motivation for implementing automation is to reduce the cognitive workload of the operator. Unfortunately, it is not guaranteed that this will happen, and automation can even have the opposite effect when workload is at its highest (Bainbridge 1983; Endsley 1996). Thus, one

of the main concerns with automated vehicles is how to manage the transfer of control to and from the automation.

There are essentially two ways to mitigate the OOTL performance problem. The first is to reduce automation errors to the point that no sudden transfers are required, and the second is to employ the concept of adaptive automation (Hancock 2007). Kaber and Endsley (among others) developed a detailed taxonomy for levels of automation and applied it to their research in the effects of adaptive automation on performance, situational awareness, and workload (Kaber and Endsley 1997; Kaber and Endsley 2004). Their taxonomy divides the space into four different functions that must be allocated to either the human or the automation. They are: monitoring system displays, generating options and strategies, selecting among various options, and implementing the chosen option.

All the levels and functions are summarized in Table 4.2. In an adaptive automation scheme, the level of automation (LOA) is varied over time, either following some rule or based on feedback from the operator. It has been found that periods of low LOA do produce better performance, while periods of intermediate LOA result in better situational awareness in a dual-task experiment, as compared to either fully manual or fully automated conditions. It was also found that if the automation could take over the primary task for a large percentage of time, then workload was reduced, and the operator's perceptual resources were freed up for different activities. Beyond the dynamic aspect of OOTL performance degradation after transfer of control, there may be some skill degradation if the driver has been relying on the automation for a long time. This is another motivation for employing adaptive automation until we reach the goal of fully autonomous transportation systems.

Table 4.2 Level of automation taxonomy by Endsley and Kaber

Level of Automation	Functions			
	Monitoring	**Generating**	**Selecting**	**Implementing**
Manual Control	Human	Human	Human	Human
Action Support	Human/Comp	Human	Human	Human/Comp
Batch Processing	Human/Comp	Human	Human	Computer
Shared Control	Human/Comp	Human/Comp	Human	Human/Comp
Decision Support	Human/Comp	Human/Comp	Human	Computer
Blended Decision Making	Human/Comp	Human/Comp	Human/Comp	Computer
Rigid System	Human/Comp	Computer	Human	Computer
Automated Decision Making	Human/Comp	Human/Comp	Human	Computer
Supervisory Control	Human/Comp	Computer	Computer	Computer
Full Automation	Computer	Computer	Computer	Computer

4.2.2 Driver Vehicle Interface

In addition to managing the level of automation and adapting the automation to the situation, it is also important to consider how automation is presented to the operator and who has invocation authority. For example, when using automated assistance, human acceptance of a computer's suggestions was better than when the computer mandated its decisions (Clamann and Kaber 2003). Beyond the issue of automation itself, the human-machine interface (HMI), or in the case of vehicles, driver-vehicle interface (DVI), presents its own challenges of designing effective and non-distractive interfaces for warning systems and automated functions (Lee et al. 2001; Lee et al. 2002). This demands choosing appropriate display locations, colors, modalities (audio-visual, haptic), interface types (menu, conversational), etc.; and no single theory exists to create an optimal interface for a given application. An important consideration when dealing with multiple levels of automation is to maintain mode awareness (or prevent mode confusion). Consider, for example, the difference between level two and level three automation. Both allow the driver to relegate steering and pedals to the vehicle, however one requires the person to remain vigilant while the other does not. How can the DVI effectively communicate the state of the automation to the driver at all times?

4.2.3 Trust in Automation

Automation is only useful insofar as it is trusted and utilized by its operator; achieving this state of affairs can be quite difficult in practice. Technology in vehicles is changing very rapidly with various systems for safety, convenience, and infotainment being introduced by several manufacturers. Regardless of the similarity these systems bear to what will eventually be fully autonomous vehicles, the degree of trust that these systems engender from the driver will feed directly into how future automation technology is perceived.

Trust may be described as a process that pairs an expectation with a vulnerability (Lee and See 2004), the expectation being a certain level of assistance that the driver can expect to receive from the vehicle, and the vulnerability being a reliance on this assistance without monitoring its performance. If the trust relationship is distorted, then the driver may stop using the automation (disuse), or use it in an unintended manner (misuse). Since not every autonomous function needs the same level of trust, this relationship needs to be dynamically calibrated for its designed purpose. Poor calibration will result in either overtrust, leading to misuse, or distrust, leading to disuse. The trust that drivers have in their vehicles' automation functions does not fully determine the extent to which those functions are utilized. If a driver has high self-confidence in their performance during manual control, then they tend to avoid transferring control to the automation. Additionally, they are quick to take back control from the automation if trust is compromised (Lee 1992; Lee and Moray 1994).

Trust in automation is not unlike trust in other humans. We may start out very trusting of the other. Then, as mistakes are made, trust is quickly lost; however, it can be regained after a period of good performance (Dzindolet et al. 2003; Lee and Moray 1992; Muir 1987). An effective, but potentially unsafe, method of enhancing trust is to *not* provide feedback to the

operator about decisions the automation makes. Alternatively, if constant feedback is provided, along with insights into why the automation behaves as it does, then the operator is more inclined to trust the system and more forgiving when it makes mistakes. An example of an effort to provide this type of continuous and intuitive feedback resulted in a graphical adaptive cruise control (ACC) display that gave constant feedback to the driver in the form of a rhombus that varied in shape (Seppelt and Lee 2007). It was found that this display helped drivers become proactive about disengaging the ACC when their vehicle was approaching a lead vehicle.

One study that specifically looked at fully autonomous driving showed that drivers were content to rely on automation in the absence of trip time constraints, even in following situations where they may have passed the lead vehicle if in manual control (Jamson et al. 2013). Although drivers using automation tended to show more signs of fatigue, they were still able to monitor the automation and become more attentive in dense traffic. This balance of trust and attention is desirable in levels of automation leading up to fully autonomous.

4.3 Societal & Economic

4.3.1 Legal & Liability

"Automated vehicles are probably legal in the United States." So states the title of a 2012 report on the legality of automated and autonomous vehicles by Bryant Walker Smith of Stanford Law School (Smith 2012). This stands in stark contrast to an oft-repeated assertion that autonomous vehicles are illegal in all 50 states (Cowen 2011). Such confusion is typical for the early days of a new and disruptive technology like this; however, the Stanford report stands as the most comprehensive discussion to date on the topic.

Why "probably"? The United States is a party to the 1949 Geneva Convention on Road Traffic, which requires in article 8 that the driver of a vehicle shall be "at all times … able to

control it." This clause is open to interpretation and may be satisfied as long as the driver can at any time take control from the automation. It would certainly not be satisfied by a future vehicle that goes so far as to remove the steering wheel and other driver controls. This is an example of a regulation that the international community will have to amend or otherwise clarify to continue innovating in automated vehicles. A similar treaty of the 1968 Vienna Convention on Road Traffic continues to be amended and may therefore provide an important indicator of international attitudes on automation (Smith 2012).

There are currently no Federal Motor Vehicle Safety Standards (FMVSS) set forth by NHTSA or the Federal Motor Carrier Safety Administration (FMCSA) that prohibit autonomous vehicles. However, NHTSA has begun active consideration of automation and has released a policy statement on the topic (NHTSA 2013b). The policy acknowledges the challenges faced in developing performance requirements for, and ensuring the safety and security of, vehicles with increased levels of automation. As a result, NHTSA currently recommends that states do not permit operation of autonomous vehicles for purposes other than testing. This policy is open for modification as NHTSA learns more during their research on automated vehicle technology over the next few years.

In the meantime, Nevada, Florida, California, and the District of Columbia have passed bills expressly permitting and regulating the operation of autonomous vehicles. These laws differentiate use by consumers and use for testing purposes. They also address licensing and liability issues, as well as the conversion of non-autonomous vehicles to autonomous operation (Peterson 2012; Pinto 2012). It is the case, however, that existing state laws will interfere with specific applications of autonomous vehicles, such as platooning (Smith 2012). Platooning has

typically involved closely spaced vehicles and introduces confusion about who is to be considered the “driver” of each vehicle in the platoon.

The next greatest legal challenge to autonomous vehicle operation is the assignment of liability in the event of an accident (Kalra, Anderson, and Wachs 2009; Douma and Palodichuk 2012; Garza 2011; Gurney 2013; Herd 2013; Marchant and Lindor 2012). Due to the transfer of control from the human driver to the automation, there is likely to be a shift in liability from the driver to the manufacturer. This may serve to dampen the enthusiasm of manufacturers to release autonomous vehicles, even if they do ultimately reduce the overall incidence of crashes. One action that is being taken by states, as well as by NHTSA, is to require the collection of vehicle crash data via electronic data recorders (EDR). This data can be used to accurately determine who had control authority over the vehicle at the time of the crash and perhaps shed light on its cause. Additionally, NHTSA is continuing to add advanced automation technologies to the New Car Assessment Program (NCAP) ratings, and this incentivizes manufacturers to continue to add new capabilities to their vehicles (Chang, Healy, and Wood 2012).

In thinking about suitable analogues to autonomous driving, one tends towards applications such as airplane and ship auto-pilots. An article in the Seattle University Law Review online (LeValley 2013) suggests that a more apropos comparison might be to elevators. Most incidents involving auto-pilot systems are still judged to be the fault of the operator because oversight is implied and expected. On the other hand, elevators are classified as “common carriers” and held to a higher standard. It is not certain whether automated vehicles would immediately be classified as common carriers, but at some point in the vision of a self-driving fleet, they certainly would. The many shades and details of tort liability, however, are beyond the scope of this report.

Even if existing laws and regulations do not expressly prohibit autonomous driving, they can slow down their rate of innovation and deployment. Re-envisioning the driving task without a human driver is a huge paradigm shift for law-making bodies, but the discussion is underway, and the many benefits still outweigh the risks in most people's minds.

4.3.2 Security

It would not be accurate to say that there are security flaws, or holes, in today's vehicles. Rather, there is simply a lack of security altogether. Car makers rely on the difficulty with which system borders can be breached through hardwired or wireless entry points into the vehicle networks, as well as proprietary message dictionaries that are difficult to reverse engineer. Nevertheless, it is possible to overcome these difficulties and take over a vehicle (Miller and Valasek 2013; Philpot 2011; Greenberg 2013). A list of entry points for vehicle attacks is given in Table 4.3. Once entry has been gained, attacks can target the in-vehicle networks (e.g. CAN bus), or electronic control units (ECUs). Fortunately, manufacturers are taking steps to increase their security measures now that these hacks are being publicized. There is also an increasing realization that security must be a focus of future vehicles that are connected to each other and to infrastructure as well as being highly automated.

There are several types of in-vehicle networks and communication channels in modern vehicles, and each of them are vulnerable to attacks (Wolf, Weimerskirch, and Paar 2012). A very popular network is called controller area network (CAN), which is a communication channel where every node hears every message, and the messages with highest priority messages are transmitted before lower priority ones. The CAN has been around since the early 1980s, and has the ability to disconnect controllers that it deems faulty.

Table 4.3 Methods to breach vehicle security

Entry point	Weakness
Telematics	The benefit of such systems is that the car can be remotely disabled if stolen, or unlocked if the keys are inside. The weakness is that a hacker could potentially do the same.
MP3 malware	Just like software apps, MP3 files can also carry malware, especially if downloaded from unauthorized sites. These files can introduce the malware into a vehicle's network if not walled off from safety-critical systems.
Infotainment apps	Car apps are like smartphone apps…they can carry viruses and malware. If the apps are not carefully screened, or if the car's infotainment software is not securely walled off from other systems, then an attack can start with a simple app update.
Bluetooth	The system that connects your smartphone to your car can be used as another entry point into the in-vehicle network.
OBD-II	This port provides direct access to the CAN bus, and potentially every system of the car. If the CAN bus traffic is not encrypted, it is an obvious entry point to control a vehicle.
Door Locks	Locks are interlinked with other vehicle data, such as speed and acceleration. If the network allows two-way communication, then a hacker could control the vehicle through the power locks.
Tire Pressure Monitoring System	Wireless TPMS systems could be hacked from adjacent vehicles and used to identify and track a vehicle through its unique sensor ID and corrupt the sensor readings.
Key Fob	It's possible to extend the range of the key fob by an additional 30' so that it could unlock a car door before the owner is close enough to prevent an unwanted entry.

A local interconnect network (LIN) is a single wire network for communicating between sensors and actuators. It does not have the versatility of the CAN bus, but has the added feature of being able to put devices into a sleep mode, saving power. FlexRay is a higher capacity network that is error tolerant and suitable for future high-speed demands. A FlexRay network may have up to 64 nodes and supports either synchronous or asynchronous communication. Media Oriented System Transport (MOST) is a newer addition, involved in the transmission of video and audio via fiber optic cables throughout the vehicle. Media Oriented System Transport has up to 60 configurable data channels that it uses, and each message sent has a specific sender and receiver addressed. Finally, Bluetooth offers personalization of a vehicle, giving the driver the ability to integrate a phone, personal digital assistant (PDA), or laptop with some of the

vehicle's systems. All of these buses are interconnected by various bridges that transfer protocols from one system type to another.

Security in these systems has for the most part not been a major concern; priority has been given to safety and cost reduction. But due to the increasing electrification of vehicles, information security has become much more important. The Wolf paper shows how the interconnections of these buses can be easily exploited by the bridges that connect each system. Example attacks on each system are described in Table 4.4.

Table 4.4 Security vulnerabilites of in-vehicle networks

Network	Weakness
LIN	Vulnerable at a single point of attack. Can put LIN slaves to sleep or make network inoperable.
CAN	Can jam the network with bogus high-priority messages or disconnect controllers with bogus error messages.
FlexRay	Can send bogus error messages and sleep commands to disconnect or deactivate controllers.
MOST	Vulnerable to jamming attacks.
Bluetooth	Wireless networks are generally much more vulnerable to attack than wired networks. Messages can be intercepted and modified, even introducing worms and viruses.

In fact, several attacks have been demonstrated (see sidebar - *Anatomy of a hack*). The teams that conducted these studies, as well as other research groups, have proposed on-board security measures to thwart them. Wolf et al. proposed the utilization of sender authentication in combination with a public key scheme to only allow valid requests to be passed onto a network. Additionally, they propose the use of encryption and firewalls to ensure messages from lower-priority networks can't reach higher-priority ones, such as a MOST to CAN message (Wolf, Weimerskirch, and Paar 2012)

Anatomy of a hack

It is disconcerting just how vulnerable these systems can be to attack, as demonstrated by a team from the University of Washington and the University of California San Diego (Koscher et al, 2010). Starting from scratch, the team used an open-source CAN bus analyzer, CARSHARK, to reverse-engineer the communication protocol on the CAN bus lines. From there, they used a technique called "fuzzing," or transmitting partially random packets of information and analyzing the effects of those packets. By using this method of fuzzing, they were able to find codes that could be used to manipulate the engine, instrument panel cluster, lights, locks, etc. The team tested these codes on the vehicle while stationary, running at 40 mph on jacks, and driving at five mph on a runway, effectively showing that no matter the state of the vehicle, malicious commands would be accepted and could put the driver in harm's way.

The team disabled communication to the instrument panel cluster while at speed, causing a drop in displayed speed from 40 mph to zero. They could lock the car regardless of whether the key was present or not. Malware could be loaded onto a vehicle, execute a harmful command, and then erase any prior trace of itself from the system completely. In some instances, the security features that were present did not operate as expected, allowing them to disable CAN communication while in motion and to put control modules into re-flashing modes while the vehicle was running. Moreover, it was observed that telematics challenge-response codes were hardcoded in the software and not used for any sort of verification.

Encryption would be greatly beneficial in preventing unauthorized access to the network, but the process of encrypting/decrypting each message in real time can be computationally intensive. It is possible, however, to break up the cipher into smaller pieces and chain them together in subsequent messages (Nilsson, Larson, and Jonsson 2008). Software architectures

have also been proposed to securely manage infotainment applications and restrict or revoke access when tampering has been detected (Macario, Torchiano, and Violante 2009; Kim, Choi, and Chung 2012).

4.3.2.1 Securing Connected Vehicles

Vehicle to Vehicle and V2I communication is considered to be more vulnerable to attack than wired systems due to the relative ease with which a hacker can gain access to the network. Indeed, to thwart privacy concerns, one need only listen to network traffic and not even act on it. This passive form of attack may not cause havoc, but is concerning nevertheless. Active attacks, however, have the potential to do damage to the transportation network in several ways (Papadimitratos et al. 2008).

Proposed security architectures address the areas of credentials, identity, cipher key management, and secure communication. The implementation of these features would be distributed across vehicles' on-board units (OBU) as well as road-side units (RSU). Road-side units would have the ability to erase their data if tampering were detected; OBUs would potentially carry several encryption keys and be able to discard ones that may have been compromised (Papadimitratos et al. 2008). Keys can be revoked by a certificate authority, and black lists, or certificate revocation lists (CFLs) may be maintained to limit bad actors on the network. All of this can happen in local areas according to the range of the nearest RSU and the speed of the vehicle (Raya and Hubaux 2005; Hubaux, Capkun, and Luo 2004; Onishi 2012, Park et al. 2010). The concept of acting in local areas or regions is critical to keeping network traffic to manageable levels and is captured by the term "geocasting," which suggests a geographically limited version of broadcasting.

4.3.3 Privacy

Technology is progressing at such a rapid pace that sometimes it seems like issues of privacy are only noticed in the rear view mirror, and sometimes not even then. Similarly, security problems often go unresolved until an attack does serious damage or attracts public attention. This is nothing new, as technology has outpaced our ability to regulate and manage it for a long time. While we have learned enough about the potential for abuse in other technological areas to apply those lessons to the innovation of autonomous vehicles, charting the correct course will prove to be challenging and complex.

Privacy and security concerns about autonomous vehicles exist for a few reasons. Such vehicles will inevitably record and store greater amounts of data than previous vehicles (Hubaux, Capkun, and Luo 2004). They will also communicate with their environment and other vehicles more than ever before (Glancy 2012). They will of course have new levels of autonomy, independent from the human occupant. Finally, they will simply attract more attention than previous vehicles, as hackers are always drawn to new opportunities to test their prowess.

Privacy concerns can be divided into three main categories: personal autonomy, personal information, and surveillance. All relate to the nature and extent of access to an individual's personal data. All of the information that is gathered about an individual's driving record is valuable to insurance companies and could be used to set new rates and standards. GPS data about vehicle location and history could be used to learn about a driver's personal life and habits, or about a company's clientele and prospect list. The Supreme Court made it clear that anonymous driving is an important concept to defend when justices unanimously upheld that police need to obtain a warrant before they can track a driver's vehicle via GPS (Glancy 2012). Although a majority of the states have laws that require users to be notified of security breaches,

there is very little application of this law in the area of autonomous vehicles. California is one example of a state that has privacy laws that limit the capabilities of event data recorders and also limit who can access said information. Despite that, the “Third Party Doctrine” allows police to gather data from a third-party source, such as a car manufacturer that can readily access the information stored on a vehicle.

Clearly, there is a segment of the population that is willing to trade away privacy for convenience, or some perceived benefit (e.g., Amazon’s recommendation engine, Google Now, email spam filters). The Progressive Casualty Insurance company has begun to install tracking devices into vehicles that record dangerous driving patterns so they can properly assign insurance rates, ostensibly marketed to consumers as a way to earn safe driver discounts. The tradeoff between personal privacy and public security is difficult to navigate, but efforts to track data or behaviors seem to be accepted more when “anonymized” and aggregated across a population. However, people are generally quite sensitive to perceived violations of their rights (e.g., National Security Agency (NSA) surveillance). Additionally, people may not be aware of the limitations of anonymization to actually protect their privacy (Ohm 2009).

These issues have played a large role in the integration of more automation into automobiles. In order to make a smooth transition into autonomous vehicles, there needs to be a sense of trust between users and the vehicle’s security system from the time they purchase their vehicle to the time they sell it to the next owner. This concept is known as “privacy by design,” where privacy considerations are addressed from the beginning of a system’s implementation. Seven identified principles in privacy by design are identified in Table 4.5.

Table 4.5 Principles of privacy by design

Privacy Principles
Proactive not reactive
Privacy by default
Privacy embedded into the design
Full functionality (positive sum, not zero sum)
End-to-end security (full lifecycle protection)
Visibility and transparency
Respect for user privacy

These principles were instilled into the Vehicle Infrastructure Integration Privacy Policy Framework (VII Privacy Framework). This framework utilized privacy principles in the design of a nationwide DSRC network for connected vehicles, and hopefully the fruit of its efforts will become part of its eventual implementation, even though the VII Coalition that adopted it was disbanded in 2007.

Electronic data recorders collect various data from the car and can provide a valuable picture of the vehicle's state leading up to an accident (Hubaux, Capkun, and Luo 2004). Such data can be critical in the forensic analysis of crashes, but they do require collecting data that, one could argue, violate privacy protections, especially if that EDR data is stolen or abused. Some state codes have incorporated rules about the use of EDRs, and NHTSA began looking into EDRs before 2000. After two working groups and much research into their use, NHTSA proposed mandating the installation of EDRs into all light passenger vehicles by the September 1, 2014 (NHTSA 2012).

As was seen in the section on security, V2V communication poses special considerations with regard to privacy. To some extent, privacy and security are conflicting goals, since allowing anonymous actors makes it more difficult to trace attacks. Privacy can be preserved if the traffic coming from a vehicle is not seen as malevolent, i.e., obeys the rules of the network. If the expectations of the network are violated, then steps may be taken to trace that traffic and

possibly revoke its authority to transmit messages (Wu, Domingo-Ferrer, and Gonzalez-Nicolas 2010).

4.3.4 Long-Term Impacts

Autonomous vehicles are expected to have drastic impacts on society in the long term. We mention two broad areas of impact that could reshape the way we live. First, our concept of vehicle ownership is evolving over time and may evolve to the point that owning a vehicle becomes a luxury rather than a necessity. Second, and building off the first point, our notions of land use, especially in urban environments, will evolve as we convert parking spaces for other uses.

Attitudes towards ownership are changing even now. The Millennial Generation is thinking twice before making large purchases like cars and houses, given the recent downturns our economy has suffered (Weissmann 2012; Tencer 2013). This trend has car manufacturers scratching their heads trying to understand and market to this demographic. The question is whether this shift is just due to the economy or if it represents a lasting trend. Certainly, the rise of autonomous vehicles would complement this attitude and enable higher levels of independence apart from vehicle ownership. The notion of an autonomous vehicle as a rail-less PRT has been advocated as a way to increase safety, efficiency, and start building smaller cars (Folsom 2011; Folsom 2012). Moreover, autonomy could play well into the business models of innovative companies like Zipcar and Uber.

Manville and Shoup studied the statistics on population density and land use for streets and note that the picture is more complicated than it seems at first glance (Manville and Shoup 2005). One factor is that parking space is still highly regulated with strict minimums, depending on the zoning requirements. However, the prevalence of parking lots is not all due to regulation,

but also a natural response to high taxes and falling land values. It has been noted that some urban areas use up to 30% of lane area for parking, but if one counts all parking spaces in garages and vertical structures and converts them to equivalent land area, then the parking coverage for Los Angeles is a whopping 81%, the highest in the world.

On the other hand, some theorize that the advent of autonomous vehicles could unleash a new wave of latent demand and actually increase congestion on the road. Currently, vehicles use only about 11% of the length of a lane on freeways, leaving 89% unutilized (Smith 2012). Autonomous vehicles could drastically increase freeway lane usage as well as the efficiency of other types of roadways. The net effect is a reduction in the perceived cost of travel, and here is where the question arises: What will happen to demand when the transportation supply is increased? City planners will have to be vigilant to take the possibilities into account, and market-based approaches, like tolling, may help to balance the new supply-demand equilibrium. Indeed, autonomous vehicle technology may even facilitate road use charging (RUC) strategies that have been discussed for years (Grush 2013).

Chapter 5 Autonomous Vehicle Research Needs

A workshop on vehicle automation was organized by TRB and hosted by Stanford University from July 15-19, 2013. During this workshop, groups of experts convened into breakout groups and discussed and debated research needs for several of the topics covered in this report (TRB 2013). The research needs statements that were generated during those breakouts are available on the workshop website and cover dozens of specific topics that must be addressed to advance the field. The rest of this chapter will use a broad brush to summarize some of critical research needs.

5.1 Technical

For half a century, Moore's Law has governed the advances in speed and miniaturization of computers. These days, the strategy has shifted from ever-faster processors to multi-core processors, yet the law remains. This trend has enabled the continued integration of computers into vehicles, which even now could be called computers on wheels. Computing advances have made much of today's autonomous capability possible, but other advances are needed.

Current automated vehicles are not able to cope with the full range of weather in which they may find themselves. If either the sensor or the lane markings are obscured, then road-following is degraded. It may be that infrastructure solutions, such as V2I communication, are needed to solve this problem; however, advances in vehicle-based automation will also contribute. More detailed digital maps and better localization algorithms may be able to address the map correspondence problem even if lane markings are not visible. Improved vision algorithms may be able to pick up additional cues like superelevation and subtle landmarks; and improved sensors will enable measurements that have greater accuracy and resolution.

Weather also adversely affects the coefficient of friction of the road surface. The traditional advice is not to employ cruise control on roads that may be slippery because the control system may not be able to resolve the correct vehicle speed from the wheel speed if the vehicle is slipping or hydroplaning. The current solution employed by some automakers is to deactivate the automation function if excessive slipping is detected, but this state of affairs is unacceptable for future systems at levels three and four.

The cost of sensors, especially LIDAR, remains a roadblock to the commercialization of vehicle automation. We have moved from the research-grade units, found on Google Car and the like, into the first few generations of commercial units, but economies of scale have not been reached yet. Apart from just reducing costs, though, a more fundamental issue must be understood. Research vehicles have largely addressed localization and object detection through brute force. Sensor coverage is 360 degrees, and different types of sensors overlap. In contrast, consider the human driver whose field of view is relatively constrained. The human compensates by scanning the scene, incorporating cues from her other senses, and bringing to bear unrivaled cognitive processing, memory and experience. It is an open question as to how much sensor coverage is actually needed for safe driving with a given amount of processor power (a moving target). Solving this question could be the key to creating an autonomous vehicle that is affordable by the average consumer.

Artificial intelligence, in the form of probabilistic reasoning using Bayesian methods, has revolutionized vehicle automation. However, automation functions are not yet good at thinking like a human. The decisions a computer makes will still seem alien to a human passenger on occasion. More research into cognitive computing is needed to make autonomous decision making more robust, to forge a true human-machine partnership, and to give the automation a

personality that appropriately matches its human operator as well as the needs of the situation (rush hour versus Sunday drive).

Testing, verification, and validation protocols are critical to the development of any new technology that is to be widely deployed; and autonomous vehicles add a tremendous amount of complexity to the process. Modern design and test paradigms such as model based design and simulation based testing will need to be expanded to handle exponentially increasing number of test scenarios.

5.2 Human Factors

The need for effective solutions to human factors challenges of vehicle automation is upon us. All the challenges outlined in Section 4.2 converge at automation level two, and level two systems are now being sold. For the first time, a driver will be able to relegate both feet and hand controls over to the automation; and their only responsibility will be to scan the environment for hazards and monitor the automation. In the event of an automation failure, the human may need to take control with only a few seconds of notice. Only time will tell to what degree complacency and misuse will be problematic at this automation level, and to what extent skill degradation may be an issue.

Level two automated vehicles require effective DVI to make perfectly clear to the driver when the automation is and is not in effect. The sequence of cues required to transfer control to and from the automation must be choreographed to maintain safety and avoid confusion. The notion of human-automation teamwork is most apropos at level two. Continuous feedback should be provided to the driver so that she understands the limitations of the automation and how close to those limitations it is performing. Novel adaptive automation schemes should be applied to maintain vigilance and the sense of cooperation. A particularly relevant question is

too what degree is standardization of interface needed to prevent confusion when transferring from one brand of vehicle to another.

The human factors challenges begin to taper off in level three vehicles. Here drivers are allowed to truly disengage from the driving and monitoring tasks and do their own thing. Fail-to-safe modes will enable the vehicle of respond safely to automation failures, and scheduled transfers of control will have to give the driver several minutes to re-engage in the driving task. However, there is a need for novel solutions to new problems. In addition to visual, audio, and haptic cues, how can the system use posture (seat position) as a cue to disengage and re-engage the driver? How best to obtain the driver's attention when they may be asleep; and should the automation monitor the driver to determine what state the driver is in? How should the driver understand the difference between level two and level three; and how can the DVI best communicate which level it is operating in?

5.3 Legal and liability

Laws are being written at the state level to allow the use of autonomous vehicles, but there exists fundamental language at higher levels that obstructs its realization, like the vehicle control clause in the Geneva Convention. These issues will likely be resolved if the political will exists to see autonomous vehicles deployed on U.S. roads. Liability issues loom large as some of the risk transfers from the vehicle owner to the manufacturer. Even though these vehicles should significantly increase safety, it is not well-enough understood what risks, if any, they pose. Additionally, how can proper liability determination be made if the operator was misusing the technology? Insurers and regulators require statistical data to properly understand risk, and it will take time for enough data to become available.

5.4 Security

The good news about security is that there exists a wealth of knowledge about cybersecurity from other computer-related fields. Moreover, a goal of the Connected Vehicles program was to design an architecture that is at once secure and private. Commercial solutions to security problems should be accelerated, and it may be useful in this regard to support standards-making activities and public-private partnerships. There are unique research questions relating to the need to keep latency low for safety critical applications. Research along these lines has considered methods that split up encryption keys into smaller chunks to reduce packet size. After automated vehicle security has been brought up to par, security research will continuously be needed to keep ahead of the hackers.

5.5 Privacy

Social mores regarding privacy are constantly evolving, and there is a great deal of variability within the population. Some protest recent NHTSA regulatory actions regarding EDRs, while others see it as a necessary step forward. Certainly, with respect to autonomous vehicles, EDRs that keep track of current automation state stand to protect the driver in the event of automation failures as much as they may incriminate him in the event of human error.

Large questions about data ownership and privacy still need to be answered. How much data actually needs to be collected and stored? How much of this data should be sent back to the manufacturer for quality control? How much should be accessible by the owner? How much must the government have access to for traffic management purposes? How should such data be treated under search and seizure laws or for the purposes of forensic investigation? These are serious, perhaps troubling, questions, but other technology examples (spam filters and free email,

Google Now) show that consumers are willing to trade away privacy for convenience in some cases.

Chapter 6 Conclusion

After almost a century of thinking about autonomous vehicles, building them, and testing them, we are poised to realize their promise and start introducing them into the transportation system. As opposed to previous efforts that were heavily focused on infrastructure improvements, a more vehicle-based approach has been proven and adopted. Nevertheless, there is still optimism about the natural synergy that is possible between vehicle and infrastructure, and so connected vehicle technology is being developed in parallel to autonomous vehicle efforts.

The final destination of autonomous vehicles on roads, highways, and streets is being approached from opposite, yet synergistic, directions. The introduction of ADAS devices into vehicles for safety applications has incrementally evolved the sensing capability of cars and gradually stepped up the LOA. From the top down, PRT and cybercars introduced fully autonomous transportation to the world, and their capabilities are slowly expanding to operate away from guide-ways, at higher speeds, and with more intelligence.

The establishment of a taxonomy for automation levels has been enormously helpful in framing the debate and laying out the issues, and it has influenced conventional wisdom about the evolution of automated vehicles. It deserves consideration whether this "natural" progression through the levels is the best way to think about vehicle automation. Figure 6.1 shows the rolling waves of challenges that we must traverse on the path to full automation. Technically, the taxonomy makes sense; however, from other perspectives, it would be optimal to skip certain levels altogether. From a legal perspective, the thought of allowing a driver to completely disengage from the primary task of driving, yet requiring that they be available to take back manual control (level three), is a formidable hurdle and a liability nightmare. It presents

problems from a human factors perspective as well; however, level two offers the most significant human factors challenges. The driver must remain vigilant while monitoring the environment and the automation and be ready to take back control in a matter of seconds.

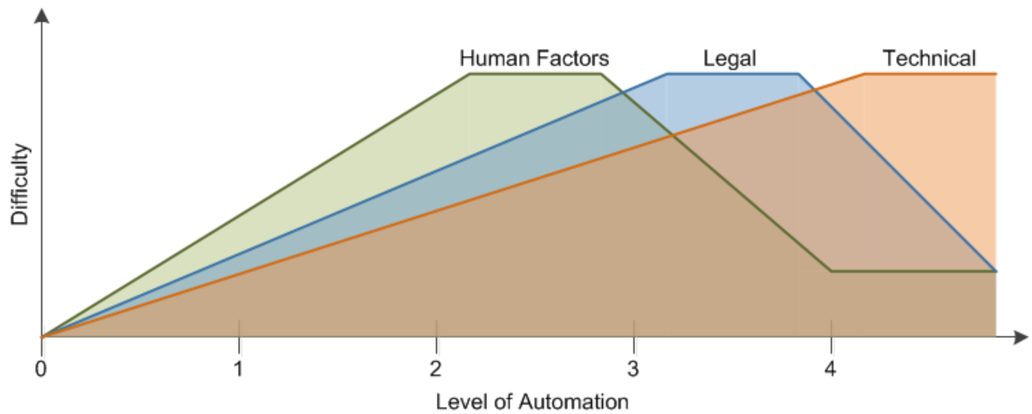


Figure 6.1 The evolution of vehicle automation and its associated challenges

Societal attitudes towards autonomous vehicles and vehicle ownership in general are likely to evolve along two paths in the coming years. Figure 6.2 shows a two-pronged hierarchy of the automation levels from two to four. Level three autonomous driving affords the driver the option of disengaging completely from the driving task or remaining engaged in the role of navigator, supervisor, and expert. This division will occur depending on the drivers' personality, their mood, the nature of the trip, and other factors.

The step to level four, fully autonomous operation, creates an even wider schism in how the driver may choose to interact with the automation (or not). First, the driver may not be the owner of the vehicle, if it is a robotic taxi, for instance. In this case, she is unlikely to take an active interest in supervising the driving or navigation. However, if the driver does own the vehicle, the relationship changes. Some percentage of drivers will cede all authority to the vehicle, just as in the case of the robotic taxi. Some, though, will demand to remain in the role of

expert, to receive feedback from the automation functions, to understand how and why the vehicle makes the decisions it does, and to take control when they wish. It is this second group that will be susceptible to feelings of alienation if the automation is not transparent enough. Further, it is likely that some aspects, such as DVIs, will have to be designed to accommodate each box in the figure in different and unique ways.

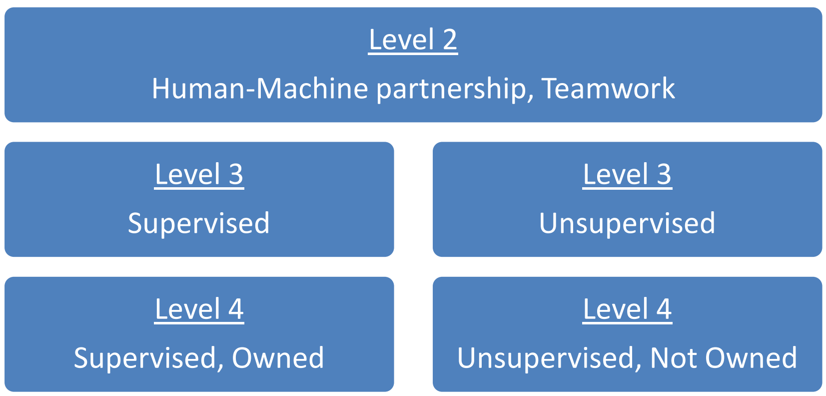


Figure 6.2 The divergent relationships with automated vehicles

The promise of autonomous vehicles has been a long time coming. Multiple cycles of innovation spurred on at various times by government funding, corporate research, and individual inspiration have persisted to bring the dream closer to reality. Exactly how soon the reality of autonomous vehicles will materialize, no one can say; however, it is hoped that when they appear, they will bring with them the promised benefits of safety, mobility, efficiency, and societal change.

Chapter 7 References

Alessandrini, A., M. Parent, and Y. Zvirin. 2009. "Evaluation of Advanced Urban Transport Systems for Sustainable Urban Mobility." *International Journal of ITS Research* 7 (1). http://trid.trb.org/view.aspx?id=907506.

Alessandrini, Adriano, Michel Null Parent, and Carlos Holguin. 2008. "Advanced City Cars, PRT and Cybercars, New Forms of Urban Transportation." In . http://hal.inria.fr/inria-00348003.

Anderson, J. Edward. 2000. "A Review of the State of the Art of Personal Rapid Transit." *Journal of Advanced Transportation* 34 (1): 3–29. doi:10.1002/atr.5670340103.

Andrews, S., and M. Cops. 2009. "Final Report: Vehicle Infrastructure Integration (VII) Proof of Concept (POC) Executive Summary - Vehicle". Final Report FHWA-JPO-09-003. Washington, DC: Research and Innovative Technology Administration.

Bailey, T., and H. Durrant-Whyte. 2006. "Simultaneous Localization and Mapping (SLAM): Part II." *IEEE Robotics Automation Magazine* 13 (3) (September): 108 –117. doi:10.1109/MRA.2006.1678144.

Bainbridge, Lisanne. 1983. "Ironies of Automation." *Automatica* 19 (6) (November): 775–779. doi:10.1016/0005-1098(83)90046-8.

Baumann, M., and J. F. Krems. 2007. "Situation Awareness and Driving: A Cognitive Model." In *Modelling Driver Behaviour in Automotive Environments*, edited by P. Carlo Cacciabue, 253–265. Springer London. http://www.springerlink.com/content/v8317k4577225l37/abstract/.

Byun, Jaemin, Myungchan Roh, Ki-In Na, Joo Chan Sohn, and Sunghoon Kim. 2012. "Navigation and Localization for Autonomous Vehicle at Road Intersections with Low-Cost Sensors." In *Intelligent Robotics and Applications*, edited by Chun-Yi Su, Subhash Rakheja, and Honghai Liu, 577–587. Lecture Notes in Computer Science 7508. Springer Berlin Heidelberg. http://link.springer.com/chapter/10.1007/978-3-642-33503-7_56.

Carlisle, Tamsin. 2010. "Masdar City Clips Another $2.5bn from Price Tag | The National." *The National*, December 1, sec. Business, Energy. http://www.thenational.ae/business/energy/masdar-city-clips-another-2-5bn-from-price-tag.

Carrasco, Juan-Pablo, Arturo de la Escalera de la Escalera, and José María Armingol. 2012. "Recognition Stage for a Speed Supervisor Based on Road Sign Detection." *Sensors* 12 (9) (September 5): 12153–12168. doi:10.3390/s120912153.

Carullo, A., and M. Parvis. 2001. "An Ultrasonic Sensor for Distance Measurement in Automotive Applications." *IEEE Sensors Journal* 1 (2): 143–. doi:10.1109/JSEN.2001.936931.

Chang, Jesse, Thomas Healy, and John Wood. 2012. "The Potential Regulatory Challenges of Increasingly Autonomous Motor Vehicles." *Santa Clara Law Review* 52 (4) (December 20): 1423.

Clamann, Michael P., and David B. Kaber. 2003. "Authority in Adaptive Automation Applied to Various Stages of Human-Machine System Information Processing." *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 47 (3) (October 1): 543–547. doi:10.1177/154193120304700361.

Cottrell, W. 2005. "Critical Review of the Personal Rapid Transit Literature." In *Automated People Movers 2005*, 1–14. American Society of Civil Engineers. http://ascelibrary.org/doi/abs/10.1061/40766%28174%2940.

Cowen, Tyler. 2011. "Can I See Your License, Registration and C.P.U.?" *The New York Times*, May 28, sec. Business Day / Economy. http://www.nytimes.com/2011/05/29/business/economy/29view.html.

Cui, Youjing, and Shuzhi Sam Ge. 2003. "Autonomous Vehicle Positioning with GPS in Urban Canyon Environments." *IEEE Transactions on Robotics and Automation* 19 (1): 15–25. doi:10.1109/TRA.2002.807557.

Dickmanns, E.D. 2002. "The Development of Machine Vision for Road Vehicles in the Last Decade." In *IEEE Intelligent Vehicle Symposium, 2002,* 1:268 – 281 vol.1. doi:10.1109/IVS.2002.1187962.

Dissanayake, M.W.M.G., P. Newman, S. Clark, H.F. Durrant-Whyte, and M. Csorba. 2001. "A Solution to the Simultaneous Localization and Map Building (SLAM) Problem." *IEEE Transactions on Robotics and Automation* 17 (3) (June): 229–241. doi:10.1109/70.938381.

Dolgov, Dmitri, Sebastian Thrun, Michael Montemerlo, and James Diebel. 2010. "Path Planning for Autonomous Vehicles in Unknown Semi-Structured Environments." *The International Journal of Robotics Research* 29 (5) (April 1): 485–501. doi:10.1177/0278364909359210.

Douma, Frank, and Sarah Aue Palodichuk. 2012. "Criminal Liability Issues Created by Autonomous Vehicles." *Santa Clara Law Review* 52 (4) (December 13): 1157.

Durrant-Whyte, H., and T. Bailey. 2006. "Simultaneous Localization and Mapping: Part I." *IEEE Robotics Automation Magazine* 13 (2) (June): 99 –110. doi:10.1109/MRA.2006.1638022.

Dzindolet, Mary T., Scott A. Peterson, Regina A. Pomranky, Linda G. Pierce, and Hall P. Beck. 2003. “The Role of Trust in Automation Reliance.” *International Journal of Human-Computer Studies* 58 (6) (June): 697–718. doi:10.1016/S1071-5819(03)00038-7.

“Electronic Highway of the Future - Science Digest (Apr, 1958).” 2013. *Modern Mechanix*. Accessed September 12. http://blog.modernmechanix.com/electronic-highway-of-the-future/.

Endsley, Mica R. 1996. “Automation and Situation Awareness.” In *Automation and Human Performance: Theory and Applications*, xx:163–181. Human Factors in Transportation. Hillsdale, NJ, England: Lawrence Erlbaum Associates, Inc.

Endsley, Mica R., and Esin O. Kiris. 1995. “The Out-of-the-Loop Performance Problem and Level of Control in Automation.” *Human Factors: The Journal of the Human Factors and Ergonomics Society* 37 (2) (June 1): 381–394. doi:10.1518/001872095779064555.

Ess, Andreas, Konrad Schindler, Bastian Leibe, and Luc Van Gool. 2010. “Object Detection and Tracking for Autonomous Navigation in Dynamic Environments.” *The International Journal of Robotics Research* 29 (14) (December 1): 1707–1725. doi:10.1177/0278364910365417.

Fleming, B. 2012. “Recent Advancement in Automotive Radar Systems [Automotive Electronics].” *IEEE Vehicular Technology Magazine* 7 (1) (March): 4 –9. doi:10.1109/MVT.2011.2180673.

Folsom, T.C. 2012. “Energy and Autonomous Urban Land Vehicles.” *IEEE Technology and Society Magazine* 31 (2): 28 –38. doi:10.1109/MTS.2012.2196339.

Folsom, Tyler. 2011. “Social Ramifications of Autonomous Urban Land Vehicles.” In Chicago.

Fouque, C., P. Bonnifait, and D. Betaille. 2008. “Enhancement of Global Vehicle Localization Using Navigable Road Maps and Dead-Reckoning.” In *Position, Location and Navigation Symposium, 2008 IEEE/ION*, 1286 –1291. doi:10.1109/PLANS.2008.4570082.

García-Garrido, Miguel A., Manuel Ocaña, David F. Llorca, Estefanía Arroyo, Jorge Pozuelo, and Miguel Gavilán. 2012. “Complete Vision-Based Traffic Sign Recognition Supported by an I2V Communication System.” *Sensors* 12 (2) (January 30): 1148–1169. doi:10.3390/s120201148.

Garza, Andrew P. 2011. “Look Ma, No Hands: Wrinkles and Wrecks in the Age of Autonomous Vehicles.” *New England Law Review* 46: 581.

Glancy, Dorothy. 2012. “Privacy in Autonomous Vehicles.” *Santa Clara Law Review* 52 (4) (December 14): 1171.

Goede, Martin, Marc Stehlin, Lukas Rafflenbeul, Gundolf Kopp, and Elmar Beeh. 2009. "Super Light Car—lightweight Construction Thanks to a Multi-Material Design and Function Integration." *European Transport Research Review* 1 (1) (March 1): 5–10. doi:10.1007/s12544-008-0001-2.

Greenberg, Andrew. 2013. "Hackers Reveal Nasty New Car Attacks." *Forbes*, August 12. http://www.forbes.com/sites/andygreenberg/2013/07/24/hackers-reveal-nasty-new-car-attacks-with-me-behind-the-wheel-video/.

Grush, Bern. 2013. "Divine Intervention: Is the Autonomous Vehicle a Saint or a Sinner for RUC?" *Tolltrans*.

Guo, Chunzhao, S. Mita, and D. McAllester. 2010. "A Vision System for Autonomous Vehicle Navigation in Challenging Traffic Scenes Using Integrated Cues." In *2010 13th International IEEE Conference on Intelligent Transportation Systems (ITSC)*, 1697 –1704. doi:10.1109/ITSC.2010.5624989.

Gurney, Jeffrey K. 2013. "Sue My Car Not Me: Products Liability and Accidents Involving Autonomous Vehicles." *University of Illinois Journal of Law, Technology & Policy*. http://works.bepress.com/jeffrey_gurney/1.

Hancock, P.A. 2007. "On the Process of Automation Transition in Multitask Human-Machine Systems." *IEEE Transactions on Systems, Man and Cybernetics, Part A: Systems and Humans* 37 (4) (July): 586 –598. doi:10.1109/TSMCA.2007.897610.

Hart, P.E., N.J. Nilsson, and B. Raphael. 1968. "A Formal Basis for the Heuristic Determination of Minimum Cost Paths." *IEEE Transactions on Systems Science and Cybernetics* 4 (2): 100–107. doi:10.1109/TSSC.1968.300136.

———. 1972. "Correction to 'A Formal Basis for the Heuristic Determination of Minimum Cost Paths.'" *SIGART Bull.* (37) (December): 28–29. doi:10.1145/1056777.1056779.

Hartman, K., and J. Strasser. 2005. "Saving Lives Through Advanced Vehicle Safety Technology: Intelligent Vehicle Initiative Final Report". Final Report FHWA-JPO-05-057. Cambridge, MA: Federal Highway Administration.

Heide, Andrea, and Klaus Henning. 2006. "The 'cognitive Car': A Roadmap for Research Issues in the Automotive Sector." *Annual Reviews in Control* 30 (2): 197–203. doi:10.1016/j.arcontrol.2006.09.005.

Herd, Alexander P. 2013. "R2DFord: Autonomous Vehicles and the Legal Implications of Varying Liability Structures." http://works.bepress.com/alexander_herd/1.

Hoc, Jean-Michel. 2001. "Towards a Cognitive Approach to Human–machine Cooperation in Dynamic Situations." *International Journal of Human-Computer Studies* 54 (4) (April): 509–540. doi:10.1006/ijhc.2000.0454.

Howard, Bill. 2013. “Frankfurt Auto Show: Mercedes Shows off Fully Autonomous S-Class, Production Cars Coming by 2020.” *ExtremeTech*. September 16. http://www.extremetech.com/extreme/166598-frankfurt-auto-show-mercedes-shows-off-fully-autonomous-s-class-production-cars-coming-by-2020.

Hubaux, J.P., S. Capkun, and Jun Luo. 2004. “The Security and Privacy of Smart Vehicles.” *IEEE Security Privacy* 2 (3): 49–55. doi:10.1109/MSP.2004.26.

James, K.P., and J.E. Craddock. 2011. “Seating System Solution for the Very Light Car.” In *2011 IEEE Systems and Information Engineering Design Symposium (SIEDS)*, 47–49. doi:10.1109/SIEDS.2011.5876853.

Jamson, A. Hamish, Natasha Merat, Oliver M.J. Carsten, and Frank C.H. Lai. 2013. “Behavioural Changes in Drivers Experiencing Highly-Automated Vehicle Control in Varying Traffic Conditions.” *Transportation Research Part C: Emerging Technologies* 30 (May): 116–125. doi:10.1016/j.trc.2013.02.008.

Johnson, T. 2013. “Enhancing Safety Through Automation”. Conference Presentation presented at the SAE Gov’t-Industry Meeting, January 31, Washington, DC. http://www.sae.org/events/gim/presentations/2013/johnson_tim.pdf.

Kaber, David B., and Mica R. Endsley. 1997. “Out-of-the-Loop Performance Problems and the Use of Intermediate Levels of Automation for Improved Control System Functioning and Safety.” *Process Safety Progress* 16 (3): 126–131. doi:10.1002/prs.680160304.

———. 2004. “The Effects of Level of Automation and Adaptive Automation on Human Performance, Situation Awareness and Workload in a Dynamic Control Task.” *Theoretical Issues in Ergonomics Science* 5 (2): 113–153. doi:10.1080/1463922021000054335.

Kalra, Nidhi, James M. Anderson, and Martin Wachs. 2009. “Liability and Regulation of Autonomous Vehicle Technologies”. Product Page. http://www.rand.org/pubs/external_publications/EP20090427.html.

Kanade, Takeo, Chuck Thorpe, and William Whittaker. 1986. “Autonomous Land Vehicle Project at CMU.” In *Proceedings of the 1986 ACM Fourteenth Annual Conference on Computer Science*, 71–80. CSC ’86. New York, NY, USA: ACM. doi:10.1145/324634.325197. http://doi.acm.org/10.1145/324634.325197.

Kandarpa, R., M. Chenzaie, M. Dorfman, J. Anderson, J. Marousek, I. Schworer, J. Beal, C. Anderson, T. Weil, and F. Perry. 2009. “Final Report: Vehicle Infrastructure Integration (VII) Proof of Concept (POC) Executive Summary - Infrastructure”. Final FHWA-JPO-09-038. Wash: Research and Innovative Technology Administration.

Keirstead, James, and Nilay Shah. 2013. *Urban Energy Systems: An Integrated Approach*. Abingdon, Oxon; New York, NY: Routledge.

Kim, Ho-Yeon, Young-Hyun Choi, and Tai-Myoung Chung. 2012. "REES: Malicious Software Detection Framework for MeeGo-In Vehicle Infotainment." In *2012 14th International Conference on Advanced Communication Technology (ICACT)*, 434–438.

Kim, Sang-Hwan, David B. Kaber, and Carlene M. Perry. 2007. "Computational GOMSL Modeling towards Understanding Cognitive Strategy in Dual-Task Performance with Automation." *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 51 (12) (October 1): 802–806. doi:10.1177/154193120705101206.

Klotz, M., and H. Rohling. 2000. "24 GHz Radar Sensors for Automotive Applications." In *13th International Conference on Microwaves, Radar and Wireless Communications. 2000. MIKON-2000*, 1:359–362 vol.1. doi:10.1109/MIKON.2000.913944.

Laursen, Lucan. 2013. "Volvo to Test Self-Driving Cars in Traffic". IEEE Spectrum. *IEEE Spectrum*. December 3. http://spectrum.ieee.org/tech-talk/green-tech/advanced-cars/volvo-to-test-selfdriving-cars-in-traffic.

Lee, John D. 1992. "Trust, Self-Confidence, and Operators' Adaptation to Automation". University of Illinois. http://hdl.handle.net/2142/23766.

Lee, John D., Brent Caven, Steven Haake, and Timothy L. Brown. 2001. "Speech-Based Interaction with In-Vehicle Computers: The Effect of Speech-Based E-Mail on Drivers' Attention to the Roadway." *Human Factors* 43: 631–640.

Lee, John D., Daniel McGehee, Timothy Brown, and Michelle Reyes. 2002. "Collision Warning Timing, Driver Distraction, and Driver Response to Imminent Rear-End Collisions in a High-Fidelity Driving Simulator." *Human Factors* 44 (2).

Lee, John D., and Neville Moray. 1992. "Trust, Control Strategies and Allocation of Function in Human-Machine Systems." *Ergonomics* 35 (10): 1243–1270. doi:10.1080/00140139208967392.

———. 1994. "Trust, Self-Confidence, and Operators' Adaptation to Automation." *International Journal of Human-Computer Studies* 40 (1) (January): 153–184. doi:10.1006/ijhc.1994.1007.

Lee, John D., and Katrina A. See. 2004. "Trust in Automation: Designing for Appropriate Reliance." *Human Factors: The Journal of the Human Factors and Ergonomics Society* 46 (1) (March 1): 50–80. doi:10.1518/hfes.46.1.50_30392.

Leonard, J.J., and H.F. Durrant-Whyte. 1991. "Simultaneous Map Building and Localization for an Autonomous Mobile Robot." In *IEEE/RSJ International Workshop on Intelligent*

Robots and Systems '91. 'Intelligence for Mechanical Systems, Proceedings IROS '91, 1442 –1447 vol.3. doi:10.1109/IROS.1991.174711.

LeValley, Dylan. 2013. "Autonomous Vehicle Liability - Application of Common Carrier Liability." *Seattle University Law Review Online* 36 (4).

Levinson, Jesse, Michael Montemerlo, and Sebastian Thrun. 2007. "Map-Based Precision Vehicle Localization in Urban Environments." In *Proceedings of the Robotics: Science and Systems Conference*. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.117.222&rep=rep1&type=pdf.

Li, Qing, Nanning Zheng, and Hong Cheng. 2004. "Springrobot: A Prototype Autonomous Vehicle and Its Algorithms for Lane Detection." *IEEE Transactions on Intelligent Transportation Systems* 5 (4) (December): 300 – 308. doi:10.1109/TITS.2004.838220.

Lowson, Martin. 2005. "Personal Rapid Transit for Airport Applications." *Transportation Research Record: Journal of the Transportation Research Board* 1930 (-1) (January 1): 99–106. doi:10.3141/1930-12.

Luettel, T., M. Himmelsbach, and H. -J Wuensche. 2012. "Autonomous Ground Vehicles-Concepts and a Path to the Future." *Proceedings of the IEEE* 100 (Special Centennial Issue): 1831–1839. doi:10.1109/JPROC.2012.2189803.

Macario, G., Marco Torchiano, and M. Violante. 2009. "An in-Vehicle Infotainment Software Architecture Based on Google Android." In *IEEE International Symposium on Industrial Embedded Systems, 2009. SIES '09*, 257–260. doi:10.1109/SIES.2009.5196223.

MacKinnon, D. 1975. "High Capacity Personal Rapid Transit System Developments." *IEEE Transactions on Vehicular Technology* 24 (1): 8–14. doi:10.1109/T-VT.1975.23591.

Manville, M., and D. Shoup. 2005. "Parking, People, and Cities." *Journal of Urban Planning and Development* 131 (4): 233–245. doi:10.1061/(ASCE)0733-9488(2005)131:4(233).

Manzie, Chris, Harry Watson, and Saman Halgamuge. 2007. "Fuel Economy Improvements for Urban Driving: Hybrid vs. Intelligent Vehicles." *Transportation Research Part C: Emerging Technologies* 15 (1) (February): 1–16. doi:10.1016/j.trc.2006.11.003.

Marchant, Gary, and Rachel Lindor. 2012. "The Coming Collision Between Autonomous Vehicles and the Liability System." *Santa Clara Law Review* 52 (4) (December 17): 1321.

Milanés, Vicente, David F. Llorca, Jorge Villagrá, Joshué Pérez, Carlos Fernández, Ignacio Parra, Carlos González, and Miguel A. Sotelo. 2012. "Intelligent Automatic Overtaking System Using Vision for Vehicle Detection." *Expert Systems with Applications* 39 (3) (February 15): 3362–3373. doi:10.1016/j.eswa.2011.09.024.

Miller, Charlie, and Chris Valasek. 2013. “Adventures in Automotive Networks and Control Units”. White paper. IOActive Labs Research. http://blog.ioactive.com/2013/08/car-hacking-content.html.

Montemerlo, Michael, Sebastian Thrun, Hendrik Dahlkamp, and David Stavens. 2006. “Winning the DARPA Grand Challenge with an AI Robot”. CiteSeerX. http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.94.9364.

Mueller, Katharina, and Sgouris P. Sgouridis. 2011. “Simulation-Based Analysis of Personal Rapid Transit Systems: Service and Energy Performance Assessment of the Masdar City PRT Case.” *Journal of Advanced Transportation* 45 (4): 252–270. doi:10.1002/atr.158.

Muir, Bonnie M. 1987. “Trust between Humans and Machines, and the Design of Decision Aids.” *International Journal of Man-Machine Studies* 27 (5–6) (November 12): 527–539. doi:10.1016/S0020-7373(87)80013-5.

Muir, Helen, David Jeffery, Anthony May, Antonino Tripodi, Simon Shepherd, and Torgeir Vaa. 2009. “Assessing the Contribution and the Feasibility of a Citywide Personal Rapid Transit System.” *Transportation Research Record: Journal of the Transportation Research Board* 2110 (-1) (December 1): 163–170. doi:10.3141/2110-20.

Najjar, Maan E. El, and Philippe Bonnifait. 2005. “A Road-Matching Method for Precise Vehicle Localization Using Belief Theory and Kalman Filtering.” *Autonomous Robots* 19 (2) (September 1): 173–191. doi:10.1007/s10514-005-0609-1.

NHTSA. 2008. “National Motor Vehicle Crash Causation Survey”. Report to Congress DOT HS 811 059. Washington, DC: NHTSA.

———. 2011. “USDOT Connected Vehicle Research Program: Vehicle-to-Vehicle Safety Application Research Plan”. Technical Report DOT HS 811 373. NHTSA.

———. 2012. “Federal Motor Vehicle Safety Standards: Event Data Recorders.” *Federal Register*, December 13.

———. 2013a. “Traffic Safety Facts: 2011 Data”. Traffic Safety Facts DOT HS 811 753. Washington, DC: NHTSA.

———. 2013b. “NHTSA Preliminary Statement of Policy Concerning Automated Vehicles”. NHTSA. http://www.nhtsa.gov/staticfiles/rulemaking/pdf/Automated_Vehicles_Policy.pdf.

———. 2013. “Connected Vehicles”. USDOT website. *Connected Vehicles*. Accessed November 21. http://icsw.nhtsa.gov/safercar/ConnectedVehicles/index.html.

Nilsson, D.K., U.E. Larson, and E. Jonsson. 2008. “Efficient In-Vehicle Delayed Data Authentication Based on Compound Message Authentication Codes.” In *Vehicular*

Technology Conference, 2008. VTC 2008-Fall. IEEE 68th, 1–5. doi:10.1109/VETECF.2008.259.

Ohm, Paul. 2009. “Broken Promises of Privacy: Responding to the Surprising Failure of Anonymization”. SSRN Scholarly Paper ID 1450006. Rochester, NY: Social Science Research Network. http://papers.ssrn.com/abstract=1450006.

Onishi, Hiro. 2012. “Paradigm Change of Vehicle Cyber Security.” In *2012 4th International Conference on Cyber Conflict*, 381–391. NATO CCD COE Publications, Talinn. http://www.ccdcoe.org/publications/2012proceedings/6_2_Onishi_ParadigmChangeOfVehicleCyber-Security.pdf.

Papadimitratos, P., L. Buttyan, T. Holczer, E. Schoch, J. Freudiger, M. Raya, Zhendong Ma, F. Kargl, A. Kung, and J-P Hubaux. 2008. “Secure Vehicular Communication Systems: Design and Architecture.” *IEEE Communications Magazine* 46 (11): 100–109. doi:10.1109/MCOM.2008.4689252.

Parent, M., and P. Daviet. 1996. “Automated Urban Vehicles: Towards a Dual Mode PRT (Personal Rapid Transit).” In *, 1996 IEEE International Conference on Robotics and Automation, 1996. Proceedings*, 4:3129–3134 vol.4. doi:10.1109/ROBOT.1996.509188.

Park, Youngho, Chul Sur, Chae Duk Jung, and Kyung-Hyung Rhee. 2010. “An Efficient Anonymous Authentication Protocol for Secure Vehicular Communications.” *Journal of Information Science and Engineering* 26: 785–800.

Parrilla, M., J. J. Anaya, and C. Fritsch. 1991. “Digital Signal Processing Techniques for High Accuracy Ultrasonic Range Measurements.” *IEEE Transactions on Instrumentation and Measurement* 40 (4): 759–763. doi:10.1109/19.85348.

Peterson, Robert. 2012. “New Technology - Old Law: Autonomous Vehicles and California’s Insurance Framework.” *Santa Clara Law Review* 52 (4) (December 18): 1341.

Philpot, Chris. 2011. “Can Your Car Be Hacked?” *Car and Driver*, August. http://www.caranddriver.com/features/can-your-car-be-hacked-feature.

Pinto, Cyrus. 2012. “How Autonomous Vehicle Policy in California and Nevada Addresses Technological and Non-Technological Liabilities.” *Intersect: The Stanford Journal of Science, Technology and Society* 5 (June 12). http://ojs.stanford.edu/ojs/index.php/intersect/article/view/361.

Pomerleau, D. 1995. “RALPH: Rapidly Adapting Lateral Position Handler.” In *Intelligent Vehicles ’95 Symposium., Proceedings of the*, 506–511. doi:10.1109/IVS.1995.528333.

Raya, Maxim, and Jean-Pierre Hubaux. 2005. “The Security of Vehicular Ad Hoc Networks.” In *Proceedings of the 3rd ACM Workshop on Security of Ad Hoc and Sensor Networks*, 11–21. SASN ’05. New York, NY, USA: ACM. doi:10.1145/1102219.1102223. http://doi.acm.org/10.1145/1102219.1102223.

Schneider, Martin. 2005. “Automotive Radar - Status and Trends.” In *GeMiC 2005 Proceedings*. Ulm, Germany: Robert Bosch GmbH.

Seppelt, Bobbie D., and John D. Lee. 2007. “Making Adaptive Cruise Control (ACC) Limits Visible.” *International Journal of Human-Computer Studies* 65 (3) (March): 192–205. doi:10.1016/j.ijhcs.2006.10.001.

Shaout, A., D. Colella, and S. Awad. 2011. “Advanced Driver Assistance Systems - Past, Present and Future.” In *Computer Engineering Conference (ICENCO), 2011 Seventh International*, 72 –82. doi:10.1109/ICENCO.2011.6153935.

Sheridan, T.B. 1980. “Computer Control and Human Alienation.” *Technology Review* (October): 61–73.

Sheridan, T.B., T. Vámos, and S. Aida. 1983. “Adapting Automation to Man, Culture and Society.” *Automatica* 19 (6) (November): 605–612. doi:10.1016/0005-1098(83)90024-9.

Sheridan, Thomas B., and Raja Parasuraman. 2005. “Human-Automation Interaction.” *Reviews of Human Factors and Ergonomics* 1 (1) (June 1): 89–129. doi:10.1518/155723405783703082.

Silberg, Gary, and Richard Wallace. 2012. “Self-Driving Cars: The next Revolution”. KPMG LLP. https://www.kpmg.com/US/en/IssuesAndInsights/ArticlesPublications/Documents/self-driving-cars-next-revolution.pdf.

Smith, Bryant. 2012. “Managing Autonomous Transportation Demand.” *Santa Clara Law Review* 52 (4) (December 19): 1401.

Smith, Bryant Walker. 2012. “Automated Vehicles Are Probably Legal in the United States”. The Center for Internet and Society. http://cyberlaw.stanford.edu/publications/automated-vehicles-are-probably-legal-united-states.

Stiller, C., and J. Ziegler. 2012. “3D Perception and Planning for Self-Driving and Cooperative Automobiles.” In *2012 9th International Multi-Conference on Systems, Signals and Devices (SSD)*, 1–7. doi:10.1109/SSD.2012.6198130.

Sukkarieh, S., E.M. Nebot, and H.F. Durrant-Whyte. 1999. “A High Integrity IMU/GPS Navigation Loop for Autonomous Land Vehicle Applications.” *IEEE Transactions on Robotics and Automation* 15 (3) (June): 572 –578. doi:10.1109/70.768189.

Sulkin, Maurice. 1999. “Personal Rapid Transit Déjà Vu.” *Transportation Research Record: Journal of the Transportation Research Board* 1677 (-1) (January 1): 58–63. doi:10.3141/1677-07.

Tencer, D. 2013. “Generation Y And Consumerism: Waning Interest In Car Ownership A Sign Of A Deeper Shift.” *The Huffington Post*. January 18. http://www.huffingtonpost.ca/2013/01/18/generation-y-consumerism-ownership_n_2500697.html.

Thrun, Sebastian, Mike Montemerlo, Hendrik Dahlkamp, David Stavens, Andrei Aron, James Diebel, Philip Fong, et al. 2007. “Stanley: The Robot That Won the DARPA Grand Challenge.” In *The 2005 DARPA Grand Challenge*, edited by Martin Buehler, Karl Iagnemma, and Sanjiv Singh, 36:1–43. Springer Tracts in Advanced Robotics. Springer Berlin / Heidelberg. http://www.springerlink.com/content/r01240114858137n/abstract/.

TRB. 1998. “National Automated Highway System Research Program - A Review.” *Transportation Research Board Special Report* (253). http://pubsindex.trb.org/view/1998/m/486657.

———. 2013. “Breakouts - Vehicle Automation: TRB@Stanford.” July. http://www.vehicleautomation.org/program/breakouts.

Treiber, Martin, Arne Kesting, and Christian Thiemann. 2008. “How Much Does Traffic Congestion Increase Fuel Consumption and Emissions? Applying Fuel Consumption Model to NGSIM Trajectory Data.” In . http://trid.trb.org/view.aspx?id=848721.

Urmson, C., D. Duggins, T. Jochem, D. Pomerleau, and C. Thorpe. 2008. “From Automated Highways to Urban Challenges.” In *IEEE International Conference on Vehicular Electronics and Safety, 2008. ICVES 2008*, 6 –10. doi:10.1109/ICVES.2008.4640916.

Urmson, Chris, Joshua Anhalt, Drew Bagnell, Christopher Baker, Robert Bittner, M. N. Clark, John Dolan, et al. 2008. “Autonomous Driving in Urban Environments: Boss and the Urban Challenge.” *Journal of Field Robotics* 25 (8): 425–466. doi:10.1002/rob.20255.

Velodyne. 2007. “Velodyne’s HDL-64E: A High Definition LIDAR Sensor for 3-D Applications”. White paper. Morgan Hill, CA: Velodyne Acoustics, Inc. www.velodynelidar.com.

Vijayenthiran, Viknesh. 2013. “Nissan Promises Autonomous Car By 2020: Video.” *Motor Authority*. August 27. http://www.motorauthority.com/news/1086543_nissan-promises-autonomous-car-by-2020-video.

Wang, Chieh-Chih, C. Thorpe, and S. Thrun. 2003. “Online Simultaneous Localization and Mapping with Detection and Tracking of Moving Objects: Theory and Results from a Ground Vehicle in Crowded Urban Areas.” In *IEEE International Conference on Robotics and Automation, 2003. Proceedings. ICRA ’03*, 1:842 – 849 vol.1. doi:10.1109/ROBOT.2003.1241698.

Weissmann, Jordan. 2012. “The Cheapest Generation.” *The Atlantic*, September. http://www.theatlantic.com/magazine/archive/2012/09/the-cheapest-generation/309060/.

Wikipedia. 2013. “DARPA Grand Challenge”. Wiki. *Www.wikipedia.com*. Accessed November 21. http://en.wikipedia.org/wiki/DARPA_Grand_Challenge.

Wolf, Marko, Andre Weimerskirch, and Christof Paar. 2012. “Security in Automotive Bus Systems.” In , 11–12.

Wu, Qianhong, J. Domingo-Ferrer, and U. Gonzalez-Nicolas. 2010. “Balanced Trustworthiness, Safety, and Privacy in Vehicle-to-Vehicle Communications.” *IEEE Transactions on Vehicular Technology* 59 (2): 559–573. doi:10.1109/TVT.2009.2034669.

Yang, Zhi-Fang, and Wen-Hsiang Tsai. 1999. “Viewing Corridors as Right Parallelepipeds for Vision-Based Vehicle Localization.” *IEEE Transactions on Industrial Electronics* 46 (3) (June): 653 –661. doi:10.1109/41.767075.