International Journal of Transportation Science and Technology 6 (2017) 208–216

Contents lists available at ScienceDirect

International Journal of Transportation Science and Technology

journal homepage: www.elsevier.com/locate/ijtst

Advancements, prospects, and impacts of automated driving systems

Ching-Yao Chan

California Partners for Advanced Transportation Technology Program (PATH), University of California at Berkeley, USA

ARTICLE INFO

Article history:
Received 11 January 2017
Accepted 20 July 2017
Available online 28 July 2017

ABSTRACT

Over the last decade, significant progress has been made in automated driving systems (ADS). Given the current momentum and progress, ADS can be expected to continue to advance and a variety of ADS products will become commercially available within a decade. It is envisioned that automated driving technology will lead to a paradigm shift in transportation systems in terms of user experience, mode choices, and business models. In this paper, we start with a review of the state-of-the-art in the field of ADS and their deployment paths. It is followed by a discussion of the future prospects of ADS and their effects on various aspects of the transportation field. We then identify two specific use cases of ADS where the impacts can be significant – personal mobility services and vehicle automation for aging society. A survey of impact assessment studies and the associated methodologies for evaluating ADS is given, which is followed by concluding remarks at the end of the paper.

Foreword

During the last decade, there have been considerable developments in automated driving technology. This phenomenon is exemplified by the watershed event of the DARPA Challenges in the mid-2000s, followed by increased efforts from a number of industrial players and the testing of Google self-driving cars on public roads, which induced even greater investments by a number of automotive manufacturers. Not only technological advancements have been demonstrated in many venues, several states and federal government in US have also moved forward to set up regulations and guidelines to prepare for the introduction of self-driving cars. (Center for Internet and Society, 2017; Federal Automated Vehicle Policy, 2016) Activities have intensified even more around the globe in recent years.

In the next few years, many manufacturers may begin to offer ADS that are equipped with various automation features. In the meantime, assistive or fully automated parking systems have arrived at the market as well. In addition, demonstrative operations of lower-speed shuttle vehicles in urban environment are also being put in place in many regions. Driverless cars as an option to provide personal mobility services have become a major theme in the landscape of transportation. With their anticipated impacts, ADS definitely have the potential to lead to real and far-reaching ramifications in our society.

In this paper, we first review the state-of-the-art developments in ADS. Then, we provide a perspective on the future prospects and societal benefits that will be brought about by ADS. Two use cases, personal mobility and automation for elderly

Peer review under responsibility of Tongji University and Tongji University Press.
E-mail address: cychan@berkeley.edu

http://dx.doi.org/10.1016/j.ijtst.2017.07.008
2046-0430/

users, are elaborated to describe how the respective landscape can be profoundly altered by ADS. We then offer a survey of studies on safety and societal impacts of ADS and the associated methodologies for impact assessment.

State-of-the-art of driving automation systems

In this section, we give an overview of driving automation systems, by clarifying ADS terminologies, describing the current status of the industry, and providing a perspective on the deployment paths of ADS.

Terminology for driving automation systems

SAE (Society of Automotive Engineers) in September 2016 released the latest version of SAE-J3016, *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles* (SAE J3016 Standard, 2016). The standard is adopted by NHTSA (National Highway Traffic Safety Administration) of the US Department of Transportation, and it is also accepted by major stakeholders in the automotive field. More elaborate terminology definitions can be found in the official release of the standards.

Language appearing in the media has often adopted the terms "auto-pilot", "autonomous", "self-driving", and "driverless" to refer to all types of driving automation systems, but the use of these terms can be imprecise and confusing at times. The term of "***Autonomous Vehicles (AV)***" is frequently used in media reports, but it is not included in the SAE standard. ***Automated Driving Systems (ADS)*** and ***Driving Automation Systems***, per SAE J3016, are more appropriate terminologies for a wide spectrum of functional modules to be offered in modern vehicles at various levels of automation. We choose to use **ADS** in this paper as the representative term that represents vehicle automation relevant to the discussions herein.

Current industrial status of driving automation systems

Table 1 shows collective highlights of news release or announcements from a number of major companies that are involved in ADS, regarding the projected timeline to have market-ready ADS. Most companies are advertising the introduction of autonomous vehicles by 2020 or sooner, while some also claim that by 2021 they will be ready to mass produce ADS.

Projections such as those included in the table above sometimes fail to clarify or choose not be specific about the type of automation features or operation modes in systems to be offered. However, it is apparent that the level of automation and exact capabilities of the products can differ considerably from one to another. It is important for observers to distinguish the type and level of automation features, in a seemingly unstopped stream of past and future media reports about ADS.

Selective of ADS highlights in 2016

It appears that the whole industry has reached a pivotal point in 2016, as many events have brought deployable ADS into reality and reached critical momentum in the industry. Below, we highlight a list of noteworthy events.

Table 1
Predicted market introduction of automated driving systems.

Organization	Confirmed and predicted product introduction	Predictions of readiness for autonomous vehicles
Audi/VW	2016 – Piloted Driving	Full AV by 2021
BMW	2014 – traffic jam assist 2014 – automated parking	Available by 2021
Bosch	2017 – Integrated Highway Assist 2020 – Highway Pilot	Auto Pilot by 2025
Continental		Available by 2020
Daimler-Benz	2014 – Intelligent Drive	Available by 2020
Ford	2015 – fully assisted parking	To mass produce AV in 2021
GM	2017 – Super cruise	
Google	2015 – Driverless Pod prototype	Available by 2018
Honda		Available by 2020
Hyundai		Available by 2030
Mobile Eye	2016 – technology ready for OEMs	
Nissan	2016 – traffic jam pilot 2018 – multiple lane control	Available by 2020
Tesla	2015 – Lane Assist + ACC 2016 – highly autonomous	Self-driving 2020–2025
Toyota	Mid 2010s – highly autonomous	
Volvo	2015 – traffic jam assist 2017 – Drive Me FOT in Sweden	Zero fatality cars by 2020

In US,

- A large number of new and conventional companies invested heavily in ADS technology and driverless car operations.
- Tesla, updated its Auto-Pilot systems and claimed to have hardware platforms ready for fully autonomous cars.
- Baidu, BMW, Ford and VW all announced they would be ready to produce fleets of autonomous vehicles in 2021.
- Uber started testing self-driving cars on public roads, with a driver onboard, in Pittsburg in August 2016 and then in San Francisco in December 2016 (but withdrew from SF after dispute about testing permits).
- Google continued testing of their self-driving cars in multiple sites in US, including Mountain View, California; Austin Texas; Kirkland, Washington; and Phoenix, Arizona.
- Google struck a deal with Fiat-Chrysler to produce 100 self-driving cars, and formalized its self-driving car projects into a separate entity, WAYMO (WAYMO website, 2017). WAYMO is reportedly in talks with Honda for forming a partnership.
- US DOT issued guidelines of ADS in September 2016, adopting a friendly and proactive stance regarding regulations for autonomous cars. California government released a draft regulation for the public operation of ADS and updated it in September 2016. Several other states have also passed similar regulations to entice testing or deployment of ADS.

In Asia,

- Toyota announced its investment to set up Toyota Research Institute in US, with a focus on artificial intelligence.
- Nissan-Renault continued to make announcements with a series of autonomous driving functions on their cars.
- Honda, previously quiet in this area, has elevated its activities in autonomous driving.
- Japan government invested in automation in a SIP-ADUS program and also planned demonstrations for Olympics 2020.
- Hyundai originally had a predicted market entry of 2030, but recently became more aggressive in its push into the field.
- Baidu of China reached a milestone of testing autonomous cars on public roads.

In Europe,

- European governments have invested heavily to support pursuits of autonomous technologies, with a number of projects funded either by the European community or by individual countries.
- Shuttle systems, such as CityMobil2, continued to be tested in different cities in Europe, and UK is particularly aggressive and vocal about their projects focusing on AV and ADS.
- Netherlands hosted a truck platoon competition in the summer of 2016.
- Daimler-Benz showed off their concepts cars and continued to be a leader in the field.
- Audi/VW, BMW, Bosch, HERE, and other companies continued to be active.
- Volvo readied automated vehicles for "Drive Me" program in Sweden, and also planned to do similar testing in England.
- Volvo announced that it would reach a goal of zero-fatalities. It also said that it would take full responsibility for its cars equipped with self-driving functions. The pledge was followed by similar statements from Google and Daimler.

Deployment paths of ADS

From the perspectives of introducing varying levels of driving automation to the market, there are two opposing views about how introduction of ADS products will turn out in terms of technical viability and market acceptance.

One camp advocates an evolutionary path, in which an increasing level of automation will be added into future vehicles, as the maturity of technologies gradually makes it feasible to be incorporated into the products. This path will evolve from lower levels of automation such as advanced driver assistance systems (ADAS) that are currently available in the market, and then onto higher levels of ADS. It is a belief of this camp that automation can assist drivers with driving tasks that demand high precision, fast reaction, and complex calculations. This camp also takes the view that human drivers have abilities to do well in many driving tasks and thus they ought to stay in the loop. For example, human drivers may exchange visual glances or body gestures with other drivers to communicate intentions that are still difficult to be comprehended by a machine. Furthermore, many users will still favor the choice of being able to take control of the vehicle even if automation is available. This type of deployment is often said to be "Something Everywhere," meaning that the deployed vehicles are automated to some degree but they will be available in markets everywhere. This view is depicted by the "Evolutionary" graph in Fig. 1.

The other camp, however, argues that it is virtually impossible to guarantee that drivers can be called back to resume control especially after the vehicle has been in automated modes for an extended period. For example, in SAE Level-3 systems, the driver is supposed to be receptive to alert and be ready in a few seconds to serve as a fallback to perform the dynamic driving tasks (DDT). This may prove to be a daunting challenge, as drivers may become inattentive or even incapable of performing the required tasks after being relieved of driving tasks for a long time. Some improper user behaviors have in fact even been witnessed in some commercialized Level-2 systems, where drivers are supposed to be still in charge of the object and event detection and response (OEDR) task but they intentionally misuse the system and thus putting themselves and others in risks. Thus, to avoid the difficulty of relying on user vigilance, this camp suggests that ADS must leap straight to full automation and remove the control away from the drivers completely. This view is best exemplified by the concept of Google driverless cars, for example, in which no steering wheel or pedals are present. This type of deployment

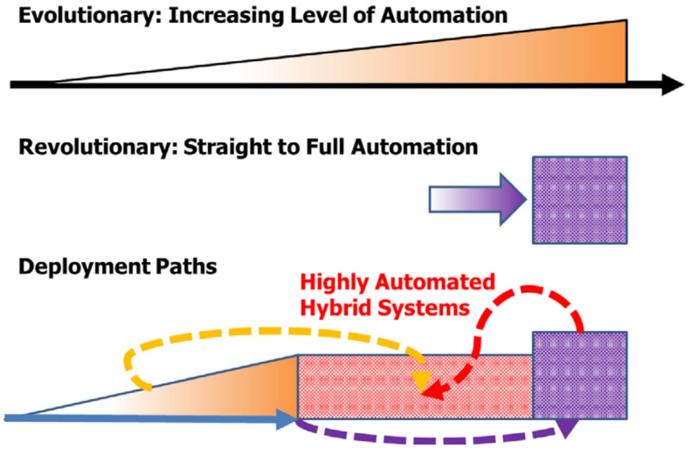

Fig. 1. Deployment paths of driving automation systems.

is often referred to as "Everything Somewhere," meaning that the vehicles are fully capable of doing everything but they only operate in some limited regions. This view is represented by as the "Revolutionary" graph in the middle portion of Fig. 1.

It is highly likely that the introduction of driving automation systems will comprise both of the two trajectories, as illustrated in the "deployment paths" graph in the bottom portion of Fig. 1. As the evolutionary approach advances and continues to overcome challenges to robustly realize the highly-automated systems with drivers in the loop, the introduction of fully ADS will also take place in selective venues. Learning from the deployment experience in both approaches and leveraging improvements in technical capabilities, highly automated hybrid systems (HAHS), in which both drivers and automation systems co-exist, will come into the market when technologies, consumers, and market are ready.

Prospects of automated driving technology

In this section, we present a perspective on future prospects of automated driving. We envision an ideal world of automated driving to explore the potential benefits enabled by ADS. Challenges for realizing ADS in a large scale are then briefly reviewed.

An ideal world of ADS

The current status and trends of developments in automated driving will doubtlessly create a wave of evolutionary transformations and simultaneously a bout of revolutionary disruptions in our society. We attempt to envision what can be accomplished by ADS in the long run, as we pursue the use of ADS. For the sake of discussions, we will put aside the deployment issues or implementation challenges that may be difficult to resolve for the moment. An exemplar set of advantages and benefits of ADS are given below, which is representative but certainly not comprehensive.

- Vehicle user perspective
    - o Fewer traffic collisions, due to elimination or minimization of human errors.
    - o More smooth and comfortable, and less stressful, rides.
    - o Greater mobility freedom for the disabled, fatigued, drunk, inattentive, senior, or children.
    - o More productive vehicle riders, and gains in personal productivity and/or pleasure.
    - o Alternative and possibly more efficient mode of transportation.
    - o Less demanding or unnecessary ownership for individuals.
    - o Feasible automated event handling in vehicle failure or incapacitated users.
- Transportation operation perspective.
    - o Reduced congestion due to reduced incidents and better managed traffic flows.
    - o More effective real-time navigation, trip assignment, and dynamic routing.
    - o More accessible, reliable and flexible shared rides for personal transit and mobility service.
    - o Reduced number of on-road vehicles via ride sharing or car sharing of automated vehicles.
    - o More efficient infrastructure, because of better vehicle control and coordinated operations.
    - o More affordable mobility services and less subsidized transit operations for public agencies.
    - o Improved economical returns and business models for private investors.
    - o More savings of resources needed for infrastructure, including parking and roadway constructions.

- Society perspective
    - o Less burden on those providing support services to mobility-challenged groups.
    - o Greater incentives for transition from personal ownership into car- and ride-sharing services.
    - o Mitigated issue of driver shortage for certain countries and regions.
    - o Reduced insurance and related ownership costs.
    - o Reduced accident rates and less societal losses.
    - o More environmentally friendly vehicles and infrastructure.
    - o Increasingly feasible transportation services of enhanced safety, reliability, security, and productivity.

Some targeted benefits in the list above are very well grounded and realistic, while other points are more difficult to quantify about the timing or extent of achievability until ADS increasingly become technically implementable and socially acceptable by the society. A report (Litman, 2013) suggests that some benefits, such as independent mobility for affluent non-drivers, may begin in the 2020s or 2030s. But most impacts, including independent mobility for low-income people (and therefore reduced need to subsidize public transport), reduced traffic congestion and parking demand (and therefore facility cost savings), increased traffic safety, energy conservation and pollution reductions, will only be significant when autonomous vehicles become affordable and represent a major portion of total vehicle travel in the 2040s through 2060s.

Regardless of the timing, the potential impacts are surely far reaching. A document by USDOT presents the long-term vision for transportation (US DOT's 30 Year Framework for the Future, 2015) and highlights vehicle automation as one of the policy directions to deal with the future challenge in transportation. In a visionary plan for London (Begg, 2014), autonomous vehicles are described as the next big revolution. Given the vigorous efforts of manufacturers and technology providers, we can expect exciting developments going forward.

Challenges of realizing automated driving

Despite the unquestionable advances in automated driving technology, it is still debatable how reliably or quickly self-driving vehicles will roam the streets in our society in the foreseeable future. Some experts in the field have different opinions about the pace of market introduction and the benefits that can be realistically expected. Technical issues are one thing, but social acceptance and driver adaptation are another matter. In the meantime, existing laws and institutional issues may hinder the progress of ADS introduction.

The introduction of automated vehicles will face many challenges. Here are a few to ponder:

- While technologies in all fronts have leapt forward tremendously, it still requires extensive developmental work to turn them into industrial products, which implies the initial production scale will be limited.
- The cost will be relatively high in initial production, which in turn makes it not available to a large population.
- The limited scale of production and deployment implies investments may not be sustained, which will lead to setback.
- Many surveys have shown the consumers are not necessarily ready to pay for the automation features, and in some cases, there is outright rejection of the notion of owning an automated vehicle.
- The paradigm shift to yield or give up the driving role to a machine and to allow machines to make decisions present a perception problem. Socially, it is not clear how (quickly) the public will embrace this new concept.
- Regulations and practices will need to adapt to the new definitions or categories of road users, role of drivers, owners, and operators of vehicles. These legal issues are not insurmountable, but they can be meaningful deterrents in the process of realizing the advocated deployment.

Summary

As can be seen in the postulated list of targeted benefits, ADS are a disruptive and powerful enabler and it has the potential to totally transform the landscape of the transportation field and affect many societal aspects beyond transportation. The list of envisioned impacts establishes the foundational goals of what ADS can do, but it also serves as a reminder that in a complex eco-system, not all objectives may be realized at the same time or in the same space. When considering deployment, there needs to be a prioritized balance of all intended objectives from a system perspective. Moreover, challenges will persist and demand a compromise or a sacrifice in the choice of desired benefits when constructing near-term and long-term plans. As we anticipate the arrival of ADS in various forms and shapes, and gauge the market readiness and public's response to ADS in coming decades, the challenge to derive the greatest returns remains an inspiration.

Exemplar use cases for ads deployment

In this section, we discuss two use cases that will be meaningfully impacted by ADS deployment – personal mobility services and vehicle automation for elderly people.

Personal mobility services

Public transit operations in US are heavily subsidized by up to 75% of expenses from government agencies. (Hess and Lombardi, 2005) Partially due to the inadequate transit infrastructure and operations in most regions in US, the reliance on personal vehicles is unsurprisingly high. According to US statistics (USDOT Bureau of Transportation Statistics, 2016), 87 percent of daily trips take place in personal vehicles. While the situation in other countries may not be as extreme as in US, the use of personal automobiles is growing at a global scale (Wikipedia, 2017).

In the meantime, there has been a demographic shift toward urbanization globally. According to a new United Nations report (World's population increasingly urban with more than half living in urban areas, 2014), 54 per cent of the world's population lives in urban areas, a proportion that is expected to increase to 66 per cent by 2050. Urbanization causes serious problems in parking, congestion, and high ownership costs for residents, travelers, and commuters. In many urban centers, making trips by public transit and taxis in many cities is a common and preferred option for travelers. However, for areas where the first- and last-mile services are non-existent or lacking, the use of transit is not an appealing option. Coupled with unsatisfactory taxi or shuttle services in some regions, ride-hailing or ride-sharing services become a well-received alternative, as evidenced by the tremendous success of mobility service companies such as UBER© and LYFT© in recent years after their entry into the market.

The global spread of coverage and popularity in personal mobility services is nothing short of phenomenal. Within a few years since inauguration, these services are now available in more than 100 countries and hundreds of cities. Many regions still resist and prohibit the operation of these services, as this new business model is causing unpleasant and disruptive changes to the old model. Nevertheless, the popular acceptance by the market is a strong statement, and on-demand personalized mobility is seen to be the mode of choice for city and local travel in the future. The original providers in the old model are already witnessing significant erosion of their market shares. Some aspects of this revolutionary transformation in the mobility sector are compared in Table 2.

Additionally, the ride-sharing sector can potentially be propelled forward by the technological breakthrough in vehicle automation in the coming decade. (Google, 2015; Uber to Put Self-Driving Cars on Pittsburgh Streets, 2018) The adoption of self-driving cars into mobility services is in a position to not only transform the transport service sector but also to upend the automotive industry. The envisioned fleet of self-driving ride service is predicted to lead to a considerable impact of vehicle sales and total vehicle numbers on the road (Driverless Cars May Cut U.S. Auto Sales 40%, 2015).

Vehicle automation for aging society

Many countries around the world are facing a demographic shift toward an aging society (Global Health and Aging, 2011). The dramatic increase in the elderly population will place new and growing demands on transport systems in many countries. Accompanying the progression of aging population, there has been an increase of older road users, which lead to significant complications in safety as well as mobility and sustainability. This is a global issue and all regions of the world are actively pursuing policies and seeking solutions to try to mitigate the challenges associated with the aging population, including:

- Mobility, for the elderly to have better access and options to fit their transportation needs.
- Disability, for the elderly to overcome their limitations in their daily lives.
- Societal responsibilities, to ease the burdens of family or society to care or assist the elderly.
- Isolation, for the elderly to continue engaging in work or social relationships.
- Traffic Safety, deterioration of driver capabilities and vulnerability of elderly road users.

From a strategic perspective, we explore transportation services, especially those enabled by vehicle automation technologies, that can be adopted for an aging society:

- Use of advanced vehicles by the older drivers.

The most direct benefit is the potential for ADS to support, enhance, and replace the driving duties of (older) drivers. Many ADAS are already helping the older drivers, and the trend of increasing automation will do more so.

- New modes of transportation modes.

Low-speed automated vehicles can become a feasible option for an elderly. Due to the limited exposure of their operating environment, in dedicated environment these vehicles will become a reality soon.

- Complementary functions of information services and automated driving.

Information services such as in-vehicle telematics functions can supplement ADS. For example, route guidance and traffic alerts provided by information services will be useful in rendering ADS more efficient. As another example, automated driving technologies will assist older drivers to react to hazardous situations at intersections or complex environment.

- Overall societal and living style changes.

For the aging population, the change in their life styles can mean that they will be less dependent on others with a degree of the freedom that is impossible today. For the overall society, this means a reduction of the burden that needs to be carried by others as a social cost.

In summary, the prospects of automated driving to contribute to the aging society are enormous. Many effective and friendly vehicular functions can be realized by a synergy of supplementary connectivity and automation (Chan et al., 2014). The availability of personalized mobility enabled by automation and life-assistance for elderly drivers to ease their burden are both monumental improvements. The overall societal impacts are not limited to the direct benefits to be reaped by the elderly only, but the ripple effects on the other groups and sectors in the community.

Impact assessment of automated driving technologies

It is commonly recognized that ADS will bring about considerable changes in many aspects of people lives. The impacts are not only related to the safety performance of individual vehicles as vehicle control transitions from human to machine, but they pertain to much greater transformations in the transportation system and the society as a whole. In this section, we present a preliminary survey of related work that aim at assessing the impacts of ADS.

Safety

Safety is a top priority concern for the public and is often cited as the number one reason to adopt automated driving technologies. For example, it can be found in numerous news reports and public agency statements that "Self-Driving cars could reduce traffic fatalities by more than 90%" (Multiple media reports, 2017). This is based on the reasoning that driver errors are assigned to be the reason in more than 90% of traffic accidents (Critical Reasons for Crashes Investigated in the National Motor Vehicle Crash Causation Survey, 2015). Such blanket statements are eye-catching, but they are neither entirely accurate nor responsible. More realistic assessment of safety benefits should take into account a variety of relevant factors.

Sivak and Schoettle (2015) discuss issues related to road safety with self-driving vehicles and presented arguments that support their conclusions: (a) The expectation of zero fatalities with self-driving vehicles is not realistic, (b) It is not a foregone conclusion that a self-driving vehicle would ever perform more safely than an experienced, middle-aged driver, (c) During the transition period when conventional and self-driving vehicles would share the road, safety might actually worsen, at least for the conventional vehicles.

Smith suggests a method (Smith, 2016) for assessing safety impacts by using proxy measures such as (a) Traffic violations (e.g., lane departure, following too closely), (b) Extreme maneuvers (e.g., sudden braking, steering, acceleration), (c) Instances where the human driver must take control, (d) Exposure to near-crash situations, and (e) Response to near-crash situations. The framework is partially based on a report (Smith et al., 2015) for estimating the potential benefits and dis-benefits of technologies. Safety modeling is based on the safety impact methodology (SIM) framework Carter et al., 2009; Najm and DaSilva, 2000, which incorporates historical crash, driver performance, and system performance data to enable a rigorous comparison of baseline and treatment vehicle crash conflicts. SIM considers changes in exposure to near-crash situations, crash prevention, and mitigation of crash severity if a crash occurs.

Another study (Kockelman et al., 2016) attempts to quantify in detail the crash-related gains of various vehicle automation and connectivity (CAV) features and anticipates their near-term and long-range impacts. The study reviews impact on safety, and specifically developed a microsimulation model (Vissim) that utilizes both human operated vehicle (HV) and AV driving models, and then estimates the number of vehicle collisions that would occur given different rates of AV market

Table 2
Transformation in Personal Mobility Service.

Operational characteristics	Convention model	New model
Service Providers	Public transit, taxis	Personal vehicles
Solution Contributors	Public transit, taxis	High-tech companies
Request and Delivery Mechanism	Fixed schedule, phone calls	Mobile app
Information Provision	Minimal, static	Instantaneous, dynamic
Service Quality	Infrequent (transit) Uneven availability (taxi)	On-demand (vs. transit) Higher availability (vs. taxi)
Business Models	Public subsidy (transit) Possible monopoly (taxi)	Privately funded or publicly traded entities
Cost Basis per Ride per Passenger	Highly subsidized (transit) Relatively high (taxi)	Slightly higher (vs. transit) Relatively low (vs. taxi)

penetration. Compiling the microsimulation outputs and Surrogate Safety Assessment Model (SSAM) safety prediction outputs, it is observed that AVs improved overall traffic system safety by a decrease in vehicle conflicts as well as the severity of the estimated crashes.

FahrenFrog (2016) proposes a process of assessing (safety) impacts by using a traffic-based approach, which is considered more comprehensive than an incident-based approach. He suggests to consider the inclusion of a realistic distribution of (highly) critical non-accident situations, the consequence of a system reaction for the surrounding traffic, and a system reaction induce into traffic. A working forum, P.E.A.R.S. (Page et al., 2015), established in 2012, to seek Worldwide harmonization and standardization, has been joined by over 30 organizations (OEMs, suppliers, research institutes, insurances, consumer protection, and governmental institutions). The implementation of selected applications is suggested to be assessed in a process that involves neutral scientific institutions, industry, and test institutes.

Rangaranjan (2016) adopts a systematic view and suggested to separate the impacts of vehicle automation into two paths: one is collision avoidance by ADAS and the other is time gain and mobility services by autonomous driving. For the ADAS benefit, an example of Low Speed AEB technology, is cited to have led to a 38% reduction in real-world rear-end crashes (Fildes et al., 2015). However, it is pointed out that more than 90% of world-wide traffic fatalities take place outside of NA, EU, Japan and Australia, where such advanced vehicular technologies are not available. It follows from such reasoning that autonomous driving is really not the answer globally to combat traffic fatalities.

Impacts beyond safety – comfort, convenience, mobility, energy, environment, and economy

Rangaranjan also looks at other benefits in time savings and enhanced mobility that are supposed to be achievable by autonomous driving. It is postulated that the impact on roadway capacity will depend on penetration rate and vehicle headway, which in turn depend on functional features of ADS. Furthermore, the ability of ADS to operate to enhance road capacity may be contradictory to the level of comfort accustomed to and desired by passengers. It is also argued that the initial introduction of ADS may decrease the road capacity due to low penetration and the conservative design of ADS behaviors.

Oshima presents a model for estimating benefits of vehicle emission by ADS, which is an extension of a predecessor international project (US-Japan-EC International Joint Report, 2013). A traffic simulation model is developed to estimate the traffic flow by the introduction of the ADS: (a) Green Wave running utilizing traffic signal information, (b) Advanced Rapid Transit (ART), (c) Truck platooning on expressways, (d) Automated driving system on expressways and general roads, (e) Last-one-mile transport by automated car and Automated valet parking.

Fagnant et al. (2015) weigh their estimates of the potential congestion and safety benefits of introducing CAVs in Texas against the costs borne by the users of the CAVs. Their work produced Benefit-Cost Ratios, for 10%, 50%, and 90% market penetration levels. Their results suggest that CAV adoption should be an excellent investment for transportation system users, as adoption rates rise.

The aforementioned report (Smith et al., 2015) by USDOT presents a framework for estimating the potential benefits and dis-benefits of technologies contributing to the automation of the Nation's surface transportation system. In addition to direct benefits in safety, mobility, energy, and environmental to the surface transportation system, ADS are also being introduced into a complex transportation system, where second-order impacts, such as the possibility of increased vehicle-miles traveled, are of significant concern. The modeling framework is suggested to ensure that multiple aspects are adequately captured. Components of the framework include (1) Safety: exposure to near-crash situations, crash prevention, and crash severity reduction; (2) Vehicle mobility: vehicle throughput, both in car following situations and at intersections; (3) Energy/environment: fuel consumption and tailpipe emissions; (4) Accessibility: personal mobility, for motorists and non-motorists; (5) Transportation system usage: response of travelers to changes in mobility and accessibility, as well as potential new modes of transportation such as increased car sharing; (6) Land use: effects of automation on land use, and (7) Economic analysis: the macro-economic impacts of all of the above changes.

Summary

With the tremendous transformations that will accompany the introduction of ADS in an increasing scale, it can be anticipated that noticeable effects will take place on user experience, traffic safety, efficiency, mobility, productivity, energy, environment, and economy. It is also evident that ADS will cause unpleasant disruptive changes in some industries, and the deployment path may not be as expedient and smooth as some proponents may wish for. Furthermore, since the real-world implementation of large-scale systems often involve compromised trade-offs among interests of various stakeholders, it will be an intriguing problem to predict the timeline of foreseen impacts to come into reality and to seek a balanced approach to achieve the greatest reward. Establishing a well-grounded and systematic evaluation framework and creating suitable and practical tools to investigate the societal benefits of ADS remain a challenging but worthy topic for future studies.

Concluding remarks

Given the aggressive investments and vigorous efforts of private industries as well as supporting activities by the governments in the last few years, we can expect to see very meaningful developments of ADS within the next decade. There is little doubt that we will see more live demonstrations and small-scale field testing of all forms of ADS around the world. A more interesting question is how many and how quickly ADS will be available to the consumers and/or operated by the service operators on public roads.

The introduction of ADS within the next decade can be anticipated to have the following components: (a) In the next few years, the market shall see increasing offerings of partial automated driving systems with lateral steering and longitudinal speed control in limited operational design domain (ODD), such as freeway pilot-driving features and assisted and automated parking systems. (b) Special low-weight, low-speed shuttle vehicles such as those demonstrated by CItyMobil2 will be deployed in a small scale in selected communities, (c) Highly automated, self-driving, or driverless vehicles such as those offered by Google, will be introduced initially as a mobility service operation, (d) Software developed for automated functions either by technology providers or automakers themselves will be increasingly incorporated into cars and become available for the mass vehicle market, (e) Special vehicle, such as buses or trucks, will be equipped with automation functions tailored for individual use cases or regional applications.

The pace of introducing and implementing automated driving in a large scale is difficult to predict in terms of their timeline. Their impacts are even harder to assess, because actual scenarios of applications and operations evolve as many social, legal, and technical factors will influence the outcome. However, with imminent introduction of highly automated vehicles within the next 5–10 years, this upcoming decade will be very illuminative as we anxiously await the arrival of the new generation of vehicles.

References

Begg, D., 2014. A 2050 Vision for London: What are the Implications for Driverless Transport, June 2014.
Carter, A.A. et al., 2009. Safety Impact Methodology (SIM): Evaluation of Performance Systems.
The Center for Internet and Society, Stanford University, Automated Driving, Legislative and Regulatory Action. http://cyberlaw.stanford.edu/wiki/index.php/Automated_Driving:_Legislative_and_Regulatory_Action. (Accessed in July 2017).
Chan, C.-Y., Oda, T., Koga, M., 2014. Vehicle Connectivity and Automation for Aging Society. ITS Europe, Helsinki, Finland.
Critical Reasons for Crashes Investigated in the National Motor Vehicle Crash Causation Survey, 2015. DOT HS 812 115, Feb. 2015.
Driverless Cars May Cut U.S. Auto Sales 40%, 2015. *Bloomberg*, May 19, 2015. http://www.bloomberg.com/news/articles/2015-05-19/driverless-cars-may-cut-u-s-auto-sales-by-40-barclays-says.
Fagnant et al, 2015. Preparing a Nation for Autonomous Vehicles: Opportunities, Barriers and Policy Recommendations for Capitalizing on Self-Driving Cars.
FahrenFrog, F., 2016. Impact Assessment, 3nd SIP-adus Workshop, Nov. 2016.
Federal Automated Vehicle Policy. https://www.transportation.gov/AV. (September 2016).
Fildes, B., et al., 2015. Effectiveness of Low Speed Autonomous Emergency Braking in Real-Life World Rear-End Crashes.
Global Health and Aging, 2011. National Institute on Aging, National Institute of Health Publication, 11–7737, October 2011.
Google vs. Uber and the race to self-driving taxis, 2015. *Media reports*, Dec. 16, 2015. http://www.theverge.com/2015/12/16/10309960/google-vs-uber-competition-self-driving-cars.
Hess, D.B., Lombardi, P.A., 2005. Governmental subsidies for public transit: history, current issues, and recent evidence. SAGE J. Public Works Policy Manage.
Kockelman, K., et al., 2016. Implications of Connected and Automated Vehicles on the Safety and Operations of Roadway Networks: A Final Report, FHWA/TX-16/0-6849-1, Aug. 2016.
Litman, T., 2013. Victoria Transport Policy Institute, Autonomous Vehicle Implementation Predictions Implications for Transport Planning, November 2013.
Multiple media reports, based on a Google search with “Self-driving cars” and “90% accidents”. (Accessed in July 2017).
Najm, W.G., DaSilva, M.P., 2000. Benefits Estimation Methodology for Intelligent Vehicle Safety Systems Based on Encounters with Critical Driving Conflicts.
Page, Y., et al., 2015. A Comprehensive and Harmonized Method or Assessing the effectiveness of ADAS by Virtual Simulation: The P.E.A.R.S. Initiative.
Rangaranjan, D., 2016. Vehicle Autonomy: what will be the impact, 3nd SIP-adus Workshop, Nov. 2016.
SAE J3016 Standard. http://standards.sae.org/j3016_201609/. (September 2016).
Sivak, M., Schoettle, B., 2015. Road Safety with Self-Driving Vehicles: General Limitations and Road Sharing with Conventional Vehicles, UMTRI-2015-2, Jan. 2015.
Smith, S., 2016. Benefits Estimation for AV Systems, 3nd SIP-adus Workshop, Nov. 2016.
Smith, S., et al., 2015. Benefits Estimation Framework for Automated Vehicle Operations, FHWA-JPO-16-229, Aug. 2015.
Uber to Put Self-Driving Cars on Pittsburgh Streets, 2018. Media reports, August 18, 2018. http://www.govtech.com/fs/transportation/Uber-to-Put-Self-Driving-Cars-on-Pittsburgh-Streets-This-Month.html.
US DOT’s 30 Year Framework for the Future, 2015, Beyond Traffic 2045, Updated: Tuesday, February 3, 2015. http://www.dot.gov/BeyondTraffic.
USDOT Bureau of Transportation Statistics, 2016. National Household Travel Survey Daily Travel Quick Facts, webpage accessed in August 2016.
US-Japan-EC International Joint Report, 2013. Guidelines for assessing the effects of ITS on CO2 Emissions.
WAYMO website. https://www.waymo.com/. (Accessed in July 2017).
Wikipedia, Motor Vehicle. https://en.wikipedia.org/wiki/Motor_vehicle. (Accessed in July 2017).
World’s population increasingly urban with more than half living in urban areas, 2014. United Nations Department of Economic and Social Affairs, July 2014.