Autonomous Vehicles

This paper is based on work completed as part of The University of Minnesota's Transportation Futures Project. More information about The Transportation Futures Project can be found on the project homepage.

INTRODUCTION

Since the early parts of the 20th century, people in the United States have sought out technologies to drive cars automatically. A demonstration in 1926 showcased a full size vehicle that was controlled by radio waves to curious onlookers in Milwaukee, Wisconsin.[1] Self-driving cars continued to be discussed on and off throughout the rest of the century as part of electric car proposals in the 1950s and the founding of Carnegie Mellon's Navlab in 1984.[2] By the early 21st century the U.S. Department of Defense started a competition for automated vehicle development. Dubbed the "DARPA Grand Challenge," the contest required driverless cars to complete a 150 mile route with the winner taking home a $1 million prize.[3] No team completed more than 5 percent of the route in the 2004 challenge, but by the 2005 competition 5 vehicles completed the challenge in its entirety – remarkable progress in just over one year.[4]

By 2007 a second Grand Challenge was developed requiring participants to navigate a 60 mile urban route to better simulate driving in towns and cities.[5] Many of the researchers who participated in university teams as part of the challenges now work for companies like Google, Uber, and others developing autonomous vehicles for commercial use.[6]

Autonomous vehicle development has continued its rapid growth since the early 2000s – leading to new classification methods and ever-evolving capabilities. The near-constant state of change in this technology makes projecting future developments or implementation timelines very difficult. Despite this, the potential for autonomous vehicles to significantly change the way that people travel in Minnesota means that understanding the consequences of adopting this technology is important when planning for the future of thestate transportation system.

LEVELS OF AUTOMATION

The U.S. DOT's National Highway Traffic Safety Administration policy on automated vehicles establishes five distinct levels of automation in vehicles.[7] Defining levels of automation provides clarity when discussing the topic among different states, product developers, and other stakeholders.

Level 0 – No-Automation

Level 0 includes all vehicles where the driver is in complete and sole control of all primary vehicle controls at all times. These include the vehicle's brakes, steering, throttle, and motive power. Many older passenger vehicles fall into this category. Vehicles that have warning systems but do not actively change the vehicle's speed or path would also be considered Level 0.[8]

[1] Milwaukee Sentinel, 1926
[2] Carnegie Mellon
[3] DARPA, 2004
[4] Levinson, 2015
[5] DARPA, 2007
[6] Levinson, 2015
[7] National Highway Traffic Safety Administration, 2013 – SAE International, an engineering organization, offers an alternative classification system with a 5th level on the fully autotomized side of the scale that is achieved when cars are 100 percent self-driving in all scenarios. For the purposes of consistency, this paper will rely on the NHTSA definitions of autonomous vehicle capabilities.
[8] Ibid.

Level 1 – Function-specific Automation

Level 1 includes automation of one or more specific control functions that operate independently in the vehicle. The driver remains in overall control of the vehicle and is responsible for safe operation, but has assistance from vehicle technology should she choose to utilize it. Common examples of level 1 automation systems include electronic stability control that prevents skids and dynamic brake control that prevents rear-end collisions. Each automated system operates independently of other automated systems, and must be allowed to act by the driver of the vehicle.

Level 2 – Combined Function Automation

Level 2, as suggested by its name, involves automation of at least two primary control functions that work together and are intended to relieve the driver of controlling those functions. Most commonly vehicles with level 2 automation combine adaptive systems like adaptive cruise control and automatic lane centering. While using level 2 automated systems the driver must be ready to re-take control from the vehicle at any time should it encounter a situation that the automated systems are not able to navigate. Vehicles with level 2 automation are available on the market today, and include Tesla's Autopilot function and General Motors' yet-to-be-released Super Cruise system.[9]

Level 3 – Limited Self-Driving Automation

Level 3 automation enables the driver to transfer all safety-critical functions to the vehicle under certain conditions. While in self-driving mode the vehicle is responsible for identifying situations which require driver assistance and alerting the driver to retake control of the vehicle. The amount of advanced warning provided before driver takeover is a key distinction between levels 2 and 3. A level 2 vehicle does not give the driver advanced notice that she needs to retake control of the vehicle, while a level 3 vehicle would provide advanced warning that allows for a transition back to no-automation mode.

Level 4 – Full Self-Driving Automation

Level 4 automated vehicles are designed to perform all safety-critical driving functions while traveling and monitor activities happening around them. Passengers in level 4 autonomous vehicles are only required to enter a destination – the vehicle takes over from there. Google's autonomous vehicle prototypes fit into the level 4 classification.

CURRENT VEHICLES & RESEARCH

The rapidly evolving autonomous vehicle landscape means that there are new advances and business moves occurring on what seems like a day-to-day basis. Tie-ins exist from vehicle technologies to the emerging concept of mobility-as-a-service (ridesharing companies like Uber and Lyft) that has the potential to entirely change the way that people travel. At the same time, connected vehicles that can exchange information with other vehicles, infrastructure, and navigational aids and supporting systems are being developed to assist with driver and vehicle communications.

Recently, President Obama announced an initiative to invest $4 billion in an effort to accelerate the development of safe vehicle automation through pilot projects that will test connected vehicle systems and work to ensure a multistate framework for connected and autonomous vehicles.[10] As part of this initiative, the National Highway Traffic Safety Administration will work to develop guidance for safe deployment and operation of autonomous vehicles, and to develop a model state policy on automated vehicles that offers a path to consistent national policy.[11]

[9] Davies, 2016
[10] USDOT, 2016
[11] Ibid.

Autonomous Vehicle Technology Roll-out

The implementation of autonomous vehicles, despite the rapid pace of technological development, will not occur overnight. Incremental progress has already been made, with level 2 autonomous vehicles already available on the market today. University of Minnesota researchers project that level 3 autonomous vehicles will be available on the market by 2020, and that level 4, fully-autonomous vehicles will be available to the public by 2025 (see Figure 1).[12] It is also hypothesized that roll-out of fully autonomous vehicles in Minnesota and other northern climates will be delayed from other parts of the United States due to challenges posed by winter driving.[13] Different companies have taken and plan to continue on different paths towards reaching level 4. Tesla has taken a more on-the-fly development approach, pushing updates to consumer vehicles to update the cars' self-driving systems, which collect driver data to continuously analyze system performance and develop additional updates.[14] Tesla has come under scrutiny for this approach given early difficulties with its Autopilot system, including its inability to judge speed limits.[15] Despite these challenges, Tesla chief executive Elon Musk believes that the Autopilot system is "probably better than a person right now" at driving.[16] According to Tesla, Autopilot navigates its surroundings using a forward radar, forward-looking camera, 12 long-range ultrasonic sensors that can sense 16 feet around the car at all speeds, and a high-precision digitally-controlled electric assist braking system in addition to GPS systems.[17] General Motors appears to be following the same trajectory as Tesla, with the launch of Cadillac's Super Cruise slated for 2017.[18]

Other players in the autonomous vehicles realm have opted to withhold from releasing incremental updates or steps along the self-driving car spectrum. Google has stated repeatedly that it is aiming squarely for level 4 autonomy before it will make its self-driving cars available in the public market, preferring to test and improve their systems in-house.[19] Google's rationale for not making incremental improvements available as Tesla has done is a belief that once drivers have stopped paying attention to the road ahead, it is much more difficult to get them to refocus and resume safe driving.[20] Google appears to not be alone in these beliefs. Ford has kept quiet on much of its own autonomous vehicle development, but is currently testing self-driving vehicles in Michigan and aims to offer a level 4 fully-autonomous car within 5 years without intermediate steps.[21]

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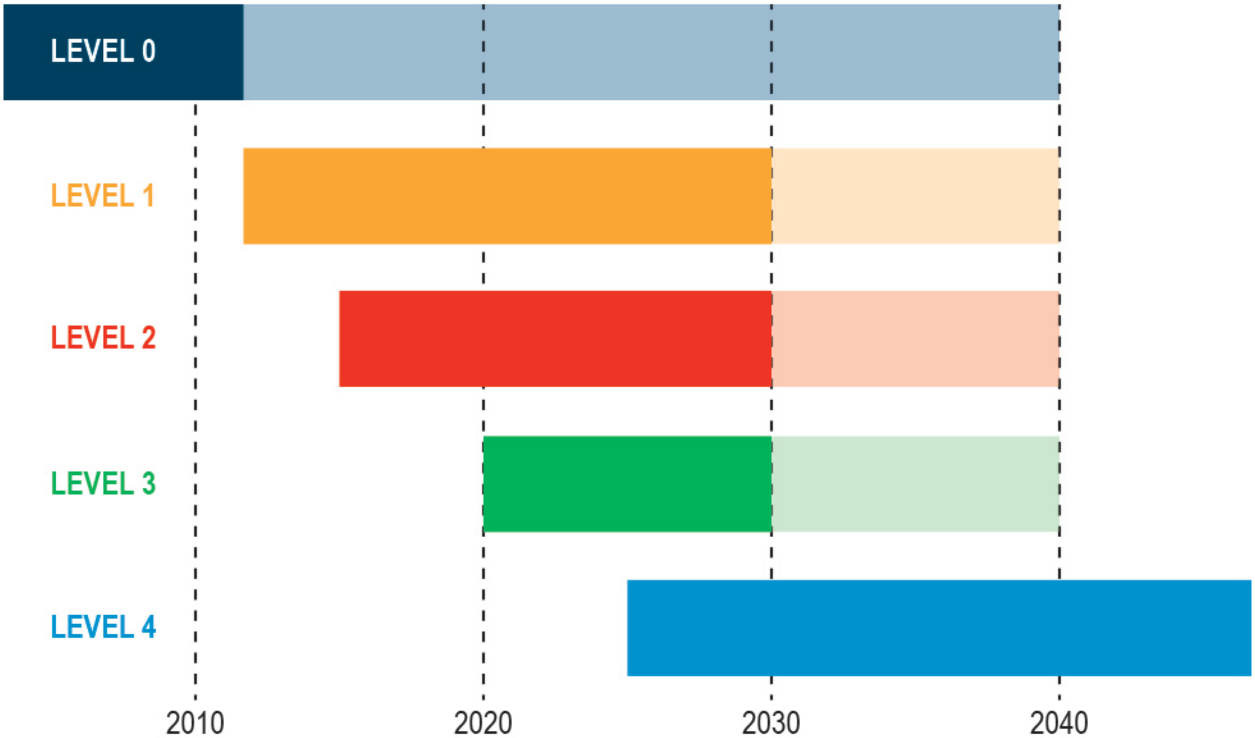
12 Levinson, 2015
13 Ibid.
14 Frankel, 2016
15 Davies, 2015
16 Frankel, 2016
17 Tesla Motors, 2015
18 Colias, 2016
19 Levinson, 2015
20 Google Self-Driving Car Monthly Report, October 2015
21 Davies, 2015

Figure 1: Projected transition through autonomous vehicle phases[22]

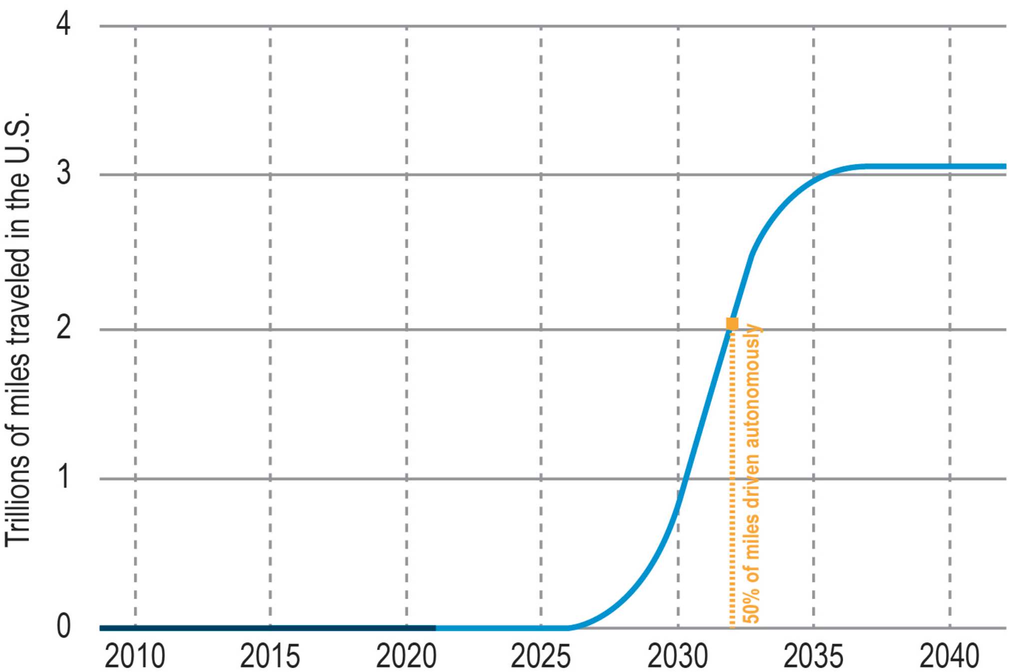


Google's autonomous vehicles navigate by using a number of different systems that interact with each other to develop redundancy and reduce the chance of incidents. Navigational instruments include lasers, radars, cameras, and GPS sensors that all work together through the vehicle's computer to move through its environment.[23]Google describes their self-driving cars as asking the four following questions to guide its movement: Where am I?; What's around me?; What will happen next?; and, Where should I go?[24] Google's testing of their autonomous vehicle systems has been expansive, and as of December 2015 the company has driven more than 1.3 million miles in autonomous mode since testing began in 2009.[25]

According to researchers at the University of Minnesota, level 4 autonomous vehicles will be available on the market as soon as 2025. Given their anticipated safety benefits, the researchers also theorize that total autonomy will be required in all new vehicles by 2030, and that as of 2040 human drivers will not be allowed to drive except in special circumstances.[26] Figure 2 shows the research teams projections of miles driven by autonomous vehicles in the United States through the early 2040s.

[22] Levinson, 2015
[23] Google Self-Driving Car Project
[24] Google Self-Driving Car Project
[25] Google Self-Driving Car Monthly Report, December 2015
[26] Levinson, 2015

Figure 2: Projected mileage driven by autonomous vehicles in the United States[27]



Connected Vehicle Technology

Self-driving vehicles are not the only emerging technology that has the potential to significantly change how people use automobiles to get around. Connected vehicles that are able to communicate location, speed, destination, and other data with other components of a connected vehicle network could improve safety, reliability, and efficiency in the system.[28] Eventually, autonomous vehicles are likely to incorporate connected vehicle technologies.

Autonomous Heavy-Duty Vehicles

Autonomous vehicle technologies will have impacts beyond passenger travel, and are poised to impact long-haul trucking in significant ways. Mercedes-Benz has developed a prototype semi-autonomous truck that has operated in driverless mode at speeds of 50 miles per hour on German highways. The truck utilizes a system of radar detectors and cameras referred to as 'Highway Pilot' much in the same way that airplanes behave when using autopilot.[29] Daimler (Mercedes-Benz's parent company) has continued developing this software and has made significant progress in the last year. In May of 2015, Daimler announced the first semi-autonomous truck licensed for highway use in the United States.[30] The Freightliner Inspiration Truck utilizes many of the advances pioneered by its Mercedes-Benz predecessor, including variable indicator lights that are yellow when a human driver is in control and blue when Highway Pilot has been activated. The truck must be driven by a driver on local streets and through challenging conditions.

Recently, a convoy of six semi-autonomous trucks completed a 1,300 mile journey across Europe as part of the EU Truck Platooning Challenge.[31] The journey crossed 4 borders and improved fuel efficiency through improved drafting as a result of closer following distances.[32]

[27] Levinson, 2015
[28] Levinson, 2015
[29] Wysocky, 2014
[30] Daimler, 2015
[31] EU Truck Platooning Challenge
[32] DiStaslo, 2016

AUTONOMOUS VEHICLES IN THE FUTURE

Clearly, autonomous vehicle technologies have the potential to reshape not just how people travel, but how we build cities and interact with the world around us. In sum, reductions in fuel expenditures, congestion, accidents, traffic, and corresponding boosts to productivity lead Morgan Stanley to project that autonomous cars will save the US economy $1.3 trillion per year – globally savings are projected to be over $5.6 trillion.[33]

Consequences of Autonomous Vehicle Adoption

University of Minnesota researchers compiled an extensive list of outcomes that may result from widespread adoption of autonomous vehicle technologies – a summary of those outcomes follows.[34]

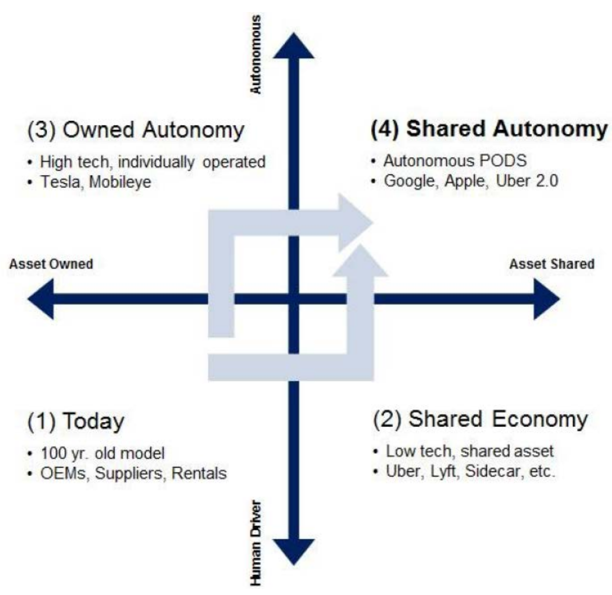
SAFETY

Because autonomous vehicles seldom get distracted or tired they are far less likely to be engaged in crashes. Upon full deployment of autonomous vehicles it is possible that total traffic deaths could fall from tens of thousands to hundreds per year. The USDOT recently proposed changes to the National Highway Traffic Safety Administration's 5-star ratings for new vehicles to include ratings for crash-avoidance advanced technologies.[35] This additional assessment will award ratings of 1 to 5 stars for a crash-avoidance system's performance, with increased weight on the vehicle's overall safety rating. Final guidelines for implementing the new crash test rating system will be released in late 2016, and testing under the new system is slated to begin on model year 2019 vehicles.

OWNERSHIP

Autonomy may make alternative vehicle ownership models more viable. It is conceivable that private ownership will fall off if consumers are able to summon a vehicle to pick them up and deliver them to their destination. Given that private automobiles are parked on average 23 out of the 24 hours in a day, it seems likely that a significant portion of people would choose to no longer own a private vehicle if a high-quality, affordable alternative existed. More discussion of potential shifts in ownership structure is covered in the Mobility as a Service trend paper. Figure 2 shows the convergence of autonomous vehicle technologies and the "sharing" economy.

Figure 3: The Four Stages of Mobility[36]



[33] Morgan Stanley, 2015
[34] Levinson, 2015
[35] NHTSA, 2015
[36] Morgan Stanley

MOBILITY FOR ALL

Autonomous vehicles offer the convenience and flexibility of personal automobile use for all, whether or not they are licensed to drive a vehicle on their own – whether by choice or due to disability. Seniors who may not want to continue driving, or children who would traditionally be considered to be too young to drive may be able to travel in autonomous vehicles, providing individualized point-to-point mobility without another driver or traditional challenges brought about by existing paratransit services.

Connected infrastructure also offers enhanced mobility for those with vision impairments. Automatic beacons and accessible maps are becoming tools to help navigate the pedestrian environment.

VEHICLE FORM

Oftentimes consumers purchase vehicles that are large enough to carry the largest possible item that they can imagine needing to transport. Depending on what kinds of ownership models emerge, it is conceivable that a person could summon a different type of vehicle depending on the purpose of their trip. Additionally, traditional vehicle forms may go by the wayside as cars are re-designed to increase the capacity of existing road infrastructure, reduce the total amount of space dedicated to roadways, or for other reasons.

PARKING

Significant reductions in the total space needed for vehicle parking and where it is located would likely occur with the adoption of autonomous vehicles. If ownership models shift and people rely more on using shared transportation services a vehicle bringing someone to the grocery store could drop them off at the front door and then complete another trip while its previous passenger summons another vehicle when they are ready to head home.

COSTS

While the cost of individual autonomous vehicles are likely to be higher than present-day non-autonomous vehicles, operational costs for maintenance, fuel, and labor in the case of taxi or ride-sharing services would be significantly lower. Full autonomous vehicle capabilities are projected to add about $10,000 to the cost of a car, but will likely decrease significantly as technologies scale in the future.[37]

ROADWAY RE-DESIGN

As vehicle forms shift and ownership models change it is conceivable that significant alterations to transportation infrastructure in cities would occur. Neighborhood streets that see low traffic volumes would no longer need parking, opening space for parks, sidewalks, bike lanes, and other creative uses. Dynamic lanes on freeways could shift directions through a message to an autonomous vehicle fleet, rather than relying on expansive signage, barricades, and warning lights. Capacity on existing roadways may be increased due to improved reaction times and potential connected vehicle technologies that minimize required following distances.

RESIDENTIAL PREFERENCES

If autonomous vehicles travel faster or more reliably and allow people to engage in other activities when traveling, it is possible that some people will continue to move further and further from their places of work in pursuit of other desired amenities. For example, it is not uncommon for people living in the Netherlands to live on opposite sides of the country from their place of work, relying on the train network to get to and from their place of employment. If emerging autonomous vehicles are driven by electric motors and rely on renewable energy sources, it is also conceivable that sprawling development may have a smaller environmental footprint than the suburbs of today.

[37] Morgan Stanley, 2015

Potential Concerns

The implementation of autonomous vehicle systems is not without potential concerns. Chief among these is data privacy and the potential of autonomous vehicle hacking. In the past, hackers have proven their ability to override and take control of vehicle systems through hard-wired connections to computers in an automobile. With the emergence of telematics systems (internet-connected automobile services) in cars comes the opportunity for hackers to remotely locate, track, or connect to a vehicle.[38] The potential implications of this vulnerability are vast, and the demand for connected vehicles seems to currently be outpacing the speed at which new, robust security measures are implemented in vehicles. Senators Edward Markey (MA) and Richard Blumenthal (CT) introduced the SPY Car Act of 2015 as a way to impose more stringent cybersecurity standards on auto-makers; however, the bill has not progressed beyond its initial reading.[39] The SPY Car Act would require the NHTSA (National Highway Traffic Safety Administration) and FTC (Federal Trade Commission) to establish performance standards for vehicle-makers that include hacking protection, data security, and hacking mitigation, while also creating a "cyber dashboard" that would display the security rating on every new car for sale.[40]

For many years to come there is likely to be a mix of human-operated and autonomous vehicles on Minnesota's roads, raising questions regarding liability, insurance, and equity. Outstanding questions regarding liability in crashes events represent an additional challenge. How fault will be determined in human-autonomous vehicle crashes and how those events in turn will affect automobile insurance practices will need to be addressed. Depending on ownership models automobile insurance as we know it today could change entirely with the adoption of autonomous vehicles. If the dominant ownership model for autonomous vehicles favors the outright purchase of each car (as is the case today) it is likely that low-income Minnesotans will not reap the same safety and convenience benefits that wealthier autonomous vehicle owners would have.

[38] Ibid.
[39] S. 1806
[40] Senator Edward J. Markey, 2015