The Human Element in Autonomous Vehicles

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Abstract. Autonomous vehicle research has been prevalent for well over a decade but only recently has there been a small amount of research conducted on the human interaction that occurs in autonomous vehicles. Although functional software and sensor technology is essential for safe operation, which has been the main focus of autonomous vehicle research, handling all elements of human interaction is also a very salient aspect of their success. This paper will provide an overview of the importance of human vehicle interaction in autonomous vehicles, while considering relevant related factors that are likely to impact adoption. Particular attention will be given to prior research conducted on germane areas relating to control in the automobile, in addition to the different elements that are expected to affect the likelihood of success for these vehicles initially developed for human operation. This paper will also include a discussion of the limited research conducted to consider interactions with humans and the current state of published functioning software and sensor technology that exists.

Keywords: Autonomous car · Autonomous vehicle · Connected car · Driverless car · Human vehicle interaction · Self-driving car

1 Introduction

Automotive and technology companies have been exploring the opportunities focused on providing consumers with a fully autonomous vehicle. Delivering such a vehicle for consumers has been identified as one of the major challenges in Computer Science [1, 2]. Related terms have been used to describe autonomous vehicles, such as self-driving car, driverless car, driverless vehicle and autonomous car; however, for the purposes of this paper an “autonomous vehicle” is one capable of performing one or more driving related tasks independently [3]. It is also important to note here that unless “fully” or “100%” autonomous is explicitly mentioned, an autonomous vehicle in the context of this survey is a vehicle with one or more of these automated, semi-autonomous or self-driving features. Human vehicle interaction for autonomous vehicles in the context of this paper is centered on the human interaction with private passenger vehicles that may or may not require human supervision. Human interaction with buses, trucks and motor bikes will be briefly discussed, but the focus is primarily on passenger cars. Automakers and technology companies are working to deliver a fully autonomous vehicle available for purchase to consumers. Companies that have publicly announced their intentions on doing research in this space include Google, Mercedes, BMW, Nissan, Volkswagen, Audi and Volvo [4, 5]. Various automotive and technology companies are racing to be the first to deliver an autonomous vehicle to their customers that can operate on all roads

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[6, 7]. Some automotive companies have publicly stated that they will be able to deliver an autonomous vehicle to consumers as early as the year 2020 [8, 9].

This survey will provide an overview of autonomous vehicles, their current state and implications. There will be a major emphasis on the importance of human vehicle interaction and control delegation in autonomous vehicles based on researchers working in this area. While human interaction in the vehicle is a vital component, this survey will also explore many other areas that are related to or likely to affect human beings based on current research in regards to autonomous vehicles. Section 1.1 of this survey will provide a general discussion around the autonomous vehicle space, advantages and disadvantages of autonomous vehicles, growth in recent years, different levels, evolution of advanced driver assistance systems and the importance of human vehicular interaction in autonomous vehicles. Section 2 provides a discussion around the current state of autonomous vehicle technology development, the eight most pressing areas related to autonomous vehicles in the literature and the lack of focus on user experience for autonomous vehicles. Section 3 discusses literature related to human-interaction and control in flight automated systems and potential areas of learning for researchers working in the autonomous vehicle space. Section 4 provides a general discussion of the suggestions going forward considering the areas related to autonomous vehicle development. Section 5 summarizes and concludes the survey.

1.1 Advantages and Disadvantages of Autonomous Vehicles

One of the major reasons behind having autonomous vehicles discussed in the literature is the emphasis on safety and their potential to significantly reduce traffic accidents that typically would have been caused by human error [3, 10–12]. Improving overall roadway safety by reducing traffic accidents has been identified as one of the biggest motivators for the development of autonomous vehicles [3, 13, 14]. According to research conducted by Klauer et al., driver inattention has been identified as the cause of almost 80% of motor vehicle accidents [15]. Driver inattention includes the driver engaging in secondary tasks, driver drowsiness, driving-related attention from the forward roadway or non-specific eye glance away from the forward roadway [15]. Many of these distraction related accidents are expected to be eliminated by the implementation of autonomous vehicles, since they do not get distracted, make significantly less errors and do not get drowsy, compared to human beings [3, 11, 14]. Another key advantage to the development of autonomous vehicles is that they would appear to be better equipped to endure the long trips that are monotonous or tiresome for human drivers [16]. On the contrary, there are many factors that may be considered negative outcomes or disadvantages resulting from the development of autonomous vehicles. One possible negative outcome, especially for driving enthusiasts, is that human-driving may eventually become illegal. Tesla's Chief Executive Officer, Elon Musk is one of the many supporters of making the operation of traditionally human-driven vehicles banned once autonomous and self-driving vehicles become widely used [17]. Various other researchers believe that human driving will eventually become illegal [9, 18]. Another possible negative impact of autonomous vehicles is that the level of expertise associated with adult drivers may decline and people may eventually become bad drivers due to the lack of actual human-controlled driving experience [19]. Loss of driving skill is likely to be a problem considering autonomous vehicles cannot independently operate on all roads and the vehicle will therefore need a human driver whenever there is a malfunction or system limitation [11, 20, 21]. Research conducted by Lu and Winter suggests that before fully autonomous vehicles are on the roadways, humans will need to supervise their automated cars [5]. Trust in the technology may become too high, security flaws related to stored driver information and personal data may increase in risk, and a vast majority of the people currently working in the public transportation sector would no longer have a job [19, 22]. It is important to note here that the loss of driving skill will not be an issue when there are only fully autonomous vehicles on roadways; however, this is likely to be an area of concern once human control is expected or required while driving [11, 20]. In other words, when the vehicle needs to return control to drivers who become too relaxed in a vehicle with automated features, driving skills will diminish as suggested by prior research [19]. Loss of driving skill is likely to be problematic on our roadways in the future when the vehicle needs to return control to human drivers who no longer remember important driving skills for safe vehicle operation [11, 20]. Subsequent sections will discuss in greater detail how other factors may affect the driving experience such as decreased situational awareness and increased cognitive workload among many others. There are many other negative consequences but these aforementioned factors are a few that have a direct impact on humans based on current research. Many factors also exist that can affect human beings, which may hinder adoption, such as legal implications, initial high cost of the technology, network or infrastructure security, changes in infrastructure, and time required for widespread adoption of autonomous vehicles [3, 9, 11, 12]. These factors will be discussed in greater detail in subsequent sections.

1.2 Source of Rapid Growth in Autonomous Vehicle Research and Development

The Defense Advanced Research Projects Agency (DARPA) is the acclaimed United States federal agency that explores seemingly impossible capabilities for new technologies [3]. DARPA hosted the first Grand Challenge in 2004 [3]. DARPA Grand Challenge participants aimed to develop an autonomous vehicle that was able to successfully navigate desert trails and roads at high speeds, which brought significant attention to autonomous vehicle development. Numerous vehicles were created by a variety of companies and universities to participate in the challenge. No vehicle was able to complete the challenge that year; however, in the following year (2005) after extensive research, a handful of vehicles were able to successfully complete the challenge [3]. Since some vehicles were actually able to complete the challenge in 2005, this demonstrated the potential for additional research in this area and hopes for autonomous vehicle researchers. DARPA later organized the Urban Challenge that took place in 2007. This was the first major large scale challenge where autonomous vehicles would need to prove themselves capable of handling a vast majority of scenarios from an urban setting as well as being able to interact with other moving

Fig. 1. Urban challenge winner 2007 from [3].

vehicles while obeying the rules of the road [3]. The Tartan racing team, which consisted of individuals from Carnegie Mellon University, General Motors, Caterpillar, Continental and Intel, won the Urban Challenge with their autonomous vehicle called "Boss", pictured in Fig. 1 below [3].

Even though the Urban Challenge was valuable for research and continuous work in this area, it had many limitations. Some of these were noted by Urmson et al., such as no pedestrians, no varied weather, and no dense traffic [3]. Other factors contributing to a potentially ungeneralizable setting included no traffic lights, only low speed testing (under 35 mph), no animals, no bicyclists or skateboarders, and only a limited subset of the rules outlined by the Department of Motor Vehicles among many others [11]. The Urban Challenge was groundbreaking but it really only had a subset of the complexity of situations that could occur in real driving environments. In spite of its limitations, the DARPA Grand challenge led to recent developments by Google on the "self-driving car" [8]. The popular work by Google on self-driving cars has brought greater attention to the feasibility of autonomous vehicles from automobile manufacturers, technology companies and other agencies building future autonomous vehicles.

1.3 Levels of Vehicle Automation

The different levels of vehicular automation have contributed to both the growth and concerns relating to autonomous vehicles [23, 24]. At the time of this publication, there is no fully autonomous vehicle available for purchase to the general public that can independently operate on all roads. However, there are vehicles with Advanced Driver Assistance Systems (ADAS) currently available for purchase that permit a driver to operate the vehicle in specific circumstances without continuous and direct human input. A Tesla is an example of such a vehicle that can temporarily control the powertrain, brake and steering via the Tesla AutoPilot feature, but carries a starting price of around $70,000 [25]. A Tesla may be too expensive for most Americans, considering top selling vehicles in the United States cost less than $27,000 [26]. According to the National Highway Traffic Safety Administration (NHTSA), there are five specific levels to the

Table 1. NHTSA autonomous vehicle levels [27].

No-Automation (Level 0)	The driver is in complete control of the primary vehicle controls
Function-specific automation (Level 1)	This involves one or more specific control functions that are independently automated, such as electronic stability control pre-charged brakes, where the vehicle automatically assists with braking to enable the driver to regain control of the vehicle or stop faster than driving alone
Combined function automation (Level 2)	Involves automation of at least two primary controls (steering, powertrain and/or brakes) functions designed to work in unison to relieve the driver of control of those functions. Lane keeping assist paired with adaptive cruise control is an example of this automation level. The driver remains fully responsible for monitoring the roadway. The automated system may need to return control to the driver with very little to no warning
Limited self-driving automation (Level 3)	Includes vehicles that allow the driver to cede full control of all safety-critical functions under certain traffic or environmental conditions to rely heavily on the vehicle to monitor for changes in those conditions eventually requiring transition back to the driver for control. The driver is expected to be available for occasional control, but with sufficiently comfortable transition time. Example is the Google self-driving car
Full self-driving automation (Level 4)	Is a vehicle designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip. The driver is not expected to be in control at any point during the trip. To date, this vehicle does not exist

different types of vehicle automation [27]. NHTSA is a part of the Executive Branch of the United States government and is also part of the Department of Transportation [27]. These automation levels created by NHTSA will be referenced throughout the entirety of this paper, since it is the governing body for transportation on roadways in the United States. These automation levels are outlined in Table 1 below:

The Society of Automotive Engineers (SAE) is a United States based global organization whose vision is to be a "leader in connecting and educating engineers while promoting, developing and advancing aerospace, commercial vehicle and automotive engineering" [28]. SAE has also defined levels of vehicular automation, which is similar but not exactly the same as NHTSA. Although these automation levels are different, NHTSA publishes some of their work in the SAE technical conferences [29]. Please see Fig. 2 below, which shows a chart of the SAE automation levels from no automation to full automation. These SAE automation levels are worth noting considering their global recognition [28] and may add more clarity to these different levels from an autonomous vehicle standpoint. It is also worth mentioning that SAE cannot directly set or change laws, as NHTSA is able to [30], therefore the SAE automation levels will not be used extensively in this paper.

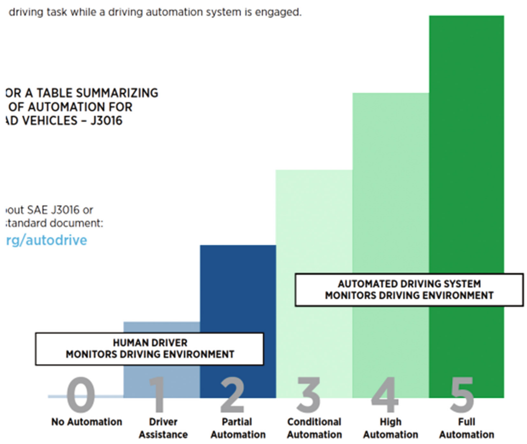

Fig. 2. SAE Levels of automation for on-road vehicles [31].

Please see Table 2 for details on what each numerical representation of the automation levels means, as defined by SAE. Again, these do not map exactly to the levels outline by NHSTA. It is also very apparent that NHTSA has 5 levels (0–4), while SAE has 6 levels (0–5).

Table 2. SAE narrative for automation levels [31].

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	*Monitoring* of Driving Environment	Fallback Performance of *Dynamic Driving Task*	System Capability *(Driving Modes)*
***Human driver* monitors the driving environment**						
0	No Automation	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	Driver Assistance	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	Partial Automation	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
***Automated driving system* ("system") monitors the driving environment**						
3	Conditional Automation	the *driving mode*-specific performance by an *automated driving system* of all aspects of the dynamic driving task with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	High Automation	the *driving mode*-specific performance by an automated driving system of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	Full Automation	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

1.4 Automobile Evolution and Advanced Driver Assistance Systems

In addition to specific levels of automation, ADAS have evolved significantly over the years from single independent systems such as Anti-Lock Braking (ABS) from the 1970s to more advanced multi feature systems today such as lane keeping, blind spot assist or adaptive cruise control [9–11]. There has been a plethora of driver assistance systems that have been released to contribute to the progression of ADAS, and the number continues to increase [9, 14]. While ADAS generally focuses on specific or a single advanced driving technology, NHTSA has outlined automation levels that center on a combination of these features and eventually full automation. Even though ADAS has undoubtedly been around before any autonomous vehicle, the work within the ADAS space has played a salient role for autonomous vehicle development, therefore an autonomous vehicle is essentially a vehicle with a plethora of ADAS features. In the past decade some the most advanced driving assistance features include single lane highway semi-autonomous driving, blind spot detection, surround view systems, park assist, forward collision warning systems, lane departure warning/lane keep assist and many others [32]. While none of these features allow the vehicle to independently operate without a human driver, some of the individual components can be used in the development of fully autonomous vehicles. For example, electronic stability control (ESC) is a relatively old ADAS feature dating back to 1987 [32]; however, it is likely that an autonomous vehicle will have such a feature or something similar that will continuously monitor steering and vehicle direction and intervene when traction with the roadway is not consistent or when skidding begins to occur [33]. Some of these individual ADAS components can help researchers working on autonomous vehicles in the sense that all parts of a fully autonomous vehicle will not need to be built from scratch and much can be learned from the ADAS technologies that already exists.

1.5 Importance of Human Vehicle Interaction

As mentioned previously, autonomous vehicles will not initially be able to handle all driving scenarios and therefore circumstances exist where control of the vehicle will need to be returned to the driver [20, 34, 35]. The literature suggests that certain operational conditions are problematic for autonomous vehicles without human input, such as construction zones, areas where an accident has recently occurred, approaching vehicles with a rare appearance, unstable road situations such as snow, detecting known objects at speeds over 81 mph, unknown objects, ice or potholes and other unexpected situations [8, 12–14]. This transition of going from the fully autonomous driving experience back to human-controlled manual driving has been noted as one of the major challenges for the producers of the fully autonomous car of tomorrow [5, 15, 16]. Human vehicle interaction in regards to human-controlled manual driving is likely to remain of major importance and a challenge until fully autonomous vehicles are able to drive on all roads [5, 20, 34, 35]. Simply put, they would need to be completely reliable without any human input, defined as a level 4 fully autonomous vehicle by NHTSA [16, 17]. Human-Computer Interaction (HCI) researchers, designers and automotive manufactures have an arduous task ahead to ensure that this human to machine experience is carefully crafted [5, 22]. Essentially, much will need to be in place to best support autonomous vehicles compared to the driving environment today, such as vehicle-to-infrastructure communication, vehicle-to-vehicle communication, policy changes, and new ways for human interaction with autonomous vehicles among others [9, 22]. The human to vehicle interaction piece is one of the most related areas to this survey paper and it has been noted in the literature that very little is known about designing interfaces for autonomous vehicles [22, 39]. The interfaces relevant to this survey in the context of autonomous vehicles will be discussed in subsequent sections. Autonomous vehicles will need the ability to recognize all possible objects or things that could be on or alongside the roadway before they can operate as truly autonomous [9, 27]. It also important to mention that even though there has been years of work on autonomous vehicles centered on the functionality of these systems, little attention has been given to the human interaction that will occur with these vehicles that humans are not familiar with [3, 5, 22]. If enough attention is not paid to human interaction, research has suggested that this could lead to unfavorable circumstances, such as mode confusion, user distrust or overreliance in automated systems, which are likely to lead to accidents [22, 40, 41].

Another salient area related to human vehicle interaction centers on how ethical situations will be handled by autonomous vehicles and how blame is assigned in the event of an accident [42–44]. Some open research questions noted in the literature by these researchers include: "what is the correct way to program an autonomous car for ethical situations? Does it matter if the potential individual(s) in a crash are adults or children? Should age be a deciding factor for survival?" [42–44]. Questions regarding liability in the event of an accident will also arise such as: "is it the fault of the car owner, vehicle manufacturer or even programmer who worked on the software" [45]. These are related to human interaction in the sense that it is unknown how much control the driver will have in these situations or if the driver will be allowed to interact with the vehicle or have a say in a potential traffic accident, based on current literature [42–44]. Although ethical situations are related to human interaction in the vehicle, the topic of ethics with be discussed in later sections.

Take-over request (TOR) is an imperative factor as it relates to human interaction with autonomous vehicles. Researchers are currently working to identify precisely when a TOR needs to be issued prior to some limitation in automation or some unexpected circumstance that the vehicle cannot handle [20, 34, 35]. Much work is still needed in this area as there is a wide array of factors to consider such as other tasks in which the driver is engaged (which is potentially a long list, as automation improvements permit drivers to look away from the forward roadway for longer periods), the speed of the vehicle, and the amount of roadway available for correction, among many others [20, 34]. A pictorial representation of a TOR is demonstrated in Fig. 3 below to provide a better understanding of the complexity of the scenario.

Prior research has demonstrated that drivers currently indulge in a plethora of distracting activities while driving such as engaging in cell phone use and interacting with the built-in information system [22]. Within these two main tasks alone, drivers perform numerous sub activities such as texting, talking, using social media, and/or adjusting the climate or radio, among many others that distract them from the immediate driving task at hand [46, 47]. Accident data suggests that people currently do

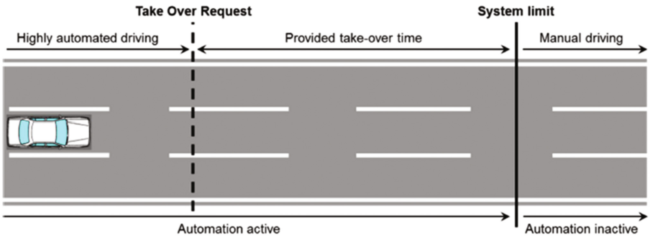

Fig. 3. Illustrative example of a TOR from [20].

more than they can handle while driving on roads today, which is evident from the 3,179 people killed and 431,000 that were injured in 2014 in the United States alone [48]. According to the NHTSA, these deaths and injuries were a direct result of distracted driving [48]. It is clear that there are distraction concerns in cars today and this is likely to increase as more and more driver assistance and autonomous features are included in automobiles. The possible combination of tasks in which the driver can engage could become even longer considering the gamut of activities drivers perform or engage with while driving. Some general examples include using a navigation system (in-vehicle or mobile), searching for an item in the car, eating a snack/meal, drinking a beverage, etc. Automation has assisted drivers in becoming safer and helping to reduce accidents, but they also make it easier for the driver to engage in secondary activities [24]. When taking into account the increase in vehicular automotive and driver assistance features in recent years, engaging in other activities while driving may become less difficult.

Take-over request (TOR) is of utmost importance here and handing over control to the driver has been identified as one of the most daunting tasks for HCI researchers, designers, and automotive manufacturers [14, 15, 17, 18, 22]. Drivers traveling at different speeds may require a different mode or process to transition back to manual driving, especially considering that the time required for the driver to take control may vary depending on the driver and/or situation. One major research challenge lies in identifying how much time a driver needs to regain control of the vehicle safely [3, 14]. Two additional factors potentially germane to this transition include the personality of the driver as well as the secondary activities in which the driver is engaged when the vehicle must return control to the driver. Research has suggested that a driver could be viewed as being in different levels of attention, such as monitoring the road ahead, drowsy, sleeping, reading a text message or email, talking on the phone, and talking to a passenger, among many others [46, 50]. Returning control to the driver is only one area that appears to be difficult to account for in all related possible situations. Autonomous driving is affected by many situations that are predictable; however, there are also unforeseeable driving situations [38]. These unforeseeable situations are intimidating due to the fact that, as an unforeseeable circumstance, the unfortunate event would have to occur in order to see the need for and apply the resolution [38]. In order to address many of these unpredictable scenarios, research suggests that continuous testing is needed for robust implementation and a more functional autonomous vehicle [1, 38]. It may be in the best interest of automakers and technology companies to account for as many of these challenging scenarios as possible through testing, prior to the release of these vehicles [38].

2 Current State and Implications of Autonomous Vehicles

2.1 Autonomous Vehicle Technology

The technology available in cars is tremendously advanced, and when considering the luxury line automakers, their technologies continue to improve. From a computing perspective, vehicles that have autonomous features are primarily dependent on GPS, cameras, laser range finders, radar and extremely accurate maps of the environment [1]. One key technology used in autonomous vehicles is a light detection and ranging (LIDAR) sensor, capable of scanning one million 3D points per second. The widely known Velodyne LIDAR sensor needed for fully autonomous vehicle operation costs between $30,000 and $85,000 for the sensor alone, which is still considerably expensive for the average consumer [3, 8, 23]. Figure 4 below provides a visual representation of the unprecedented Google self-driving car, with the Velodyne LIDAR mounted on the roof of the vehicle.

Fig. 4. Google self-driving car from [9].

To date there is no known precise combination of sensors, cameras, LIDARs and other technologies that are required to be included in all autonomous vehicles. Outside of information disclosed in a patent that a company specifically owns, novel information regarding product development details is not usually disclosed to the public as with many other new technologies [52, 53]. Google has already demonstrated capabilities of an autonomous vehicle that can drive, but as noted earlier a level 4 NHTSA vehicle that does not require any human input does not yet exist [27]. In terms of what is currently known in literature about the technologies in autonomous vehicles, they have dedicated systems for motion planning (trajectory generation, on-road navigation and zone navigation), a perception system responsible for providing a model of the world to the behavioral and motion planning subsystems (moving obstacle detection and tracking, static obstacle detection and mapping, roadmap localization and road shape estimation), mission planning (detection blockages, handling blockages), behavioral reasoning (intersections and yielding, distance keeping and merge planning, and error recovery), software infrastructure (communications library, interfaces library, configuration library, task library, debug logger and log/playback) and testing that is sometimes intertwined with the software stack [3]. Pink et al. provided a great illustration of the current main sensor technology in autonomous vehicles, in Fig. 5 below [38]. This illustration is not intended to be exhaustive; however, it provides an overview of the sensing technologies included in these vehicles. This image depicts the sensing technologies employed specifically by Bosch autonomous vehicle research division and is unlikely to be exactly the same for other companies working on autonomous vehicles. The technologies used in autonomous vehicles will vary to some degree dependent on the automotive manufacturer or technology company and the level of autonomy that the vehicle can support.

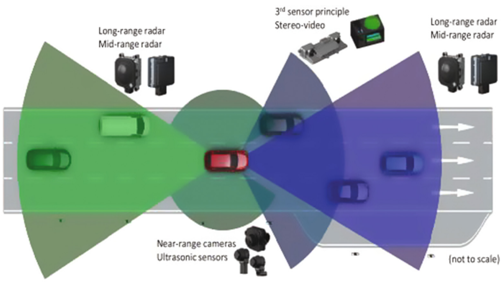

Fig. 5. Field of view of sensors for autonomous vehicles from [38].

2.2 Implications of Autonomous Vehicles

Legal Implications. Concerns around legality and responsibility are of monumental importance since accidents are likely to occur in the future where an autonomous vehicle is not being directly controlled by the driver [44]. The question is not whether accidents with autonomous vehicles will occur, but a matter of when. There have been two recent deaths when Tesla's Autopilot was engaged in addition to other accidents not resulting in deaths where AutoPilot malfunctioned. Tesla's Autopilot feature has the ability to temporally control the vehicle's powertrain, brake and steering under specific highway conditions [25]. On May 7th 2016, there was an accident that resulted in the death of a driver using Tesla's AutoPilot [54]. AutoPilot is especially relevant here since there may be direct implications on future autonomous vehicles stemming from this particular accident. In this and similar future scenarios, some open questions include: Who should be held responsible? Would it be Tesla, the dead driver of the car, the truck that collided with the Tesla, the owner of the car, or someone else? These malfunctions are increasing as advanced driver assistance features (with semi-autonomous capabilities) become prevalent. More recently, on September 14th 2016, the accident details were released of a Tesla with AutoPilot engaged that resulted in the death of a 23-year-old man [55]. The accident details by The Drive news agency included video footage showing the Tesla colliding head on with a street-cleaning truck that was stopped on the side of the road [55]. The video footage from the accident suggests that the Tesla involved in the accident drove into the street-cleaning truck at constant speed and did not appear to slow down [55]. AutoPilot malfunctions are becoming a growing problem for Tesla and potentially the entire automotive and/or technology industry. Two similar accidents (fortunately with no human deaths) have recently occurred with Tesla's AutoPilot engaged where the Tesla in question failed to notice a vehicle that was stopped on the side of the road in front of it [55–57]. The release of the news about recent Tesla accidents does inform the public about a potential system failure of Tesla's AutoPilot automated feature. The exact impact of the release of this information on public perception of autonomous vehicles is unknown. How frequently these accidents occur is likely to be a factor, since when accidents are infrequent, people may not consider these accidents with automated cars as a major problem. On the contrary if many accidents frequently occur with automated vehicles malfunctioning, this may lead to a negative association by the public with automated vehicles. Additionally, if accidents do occur but are not released to the public then automated crashes may appear as less of a problem to the public. Accidents similar to these where an automated system malfunctions could lead to some customers being concerned about the functionality of autonomous technologies, while it may lead others to completely lose faith or interest in these technologies [58]. It is unlikely that customers will be inclined to purchase a vehicle that is known to have automated features that malfunction if these accidents continue to occur. These accidents should certainly not be taken lightly by technology companies and automakers as vehicles with autonomous features are still in sensitive, growing and developing stages.

The discussion to address questions regarding liability becomes even more sensitive and convoluted depending on how all the scenarios regarding control are formalized [43, 44]. For example, when a human driver identifies danger or a forthcoming accident, action is typically taken to prevent or avoid the problem. If the vehicle is not designed to return control to the driver or the outcome of the vehicle's pre-programmed solution to the identified problem is one that the driver disagrees with-who should be held responsible? [43, 44]. The outcome refers to the multiple possibilities that an autonomous vehicle can select from for accident-prone situations. Regulators will need to account for this and all other possible scenarios of liability with autonomous vehicles.

Infrastructure Implications. The infrastructure for autonomous vehicles is related to humans in the sense that a robust and efficient infrastructure will lead to a safer driving environment and require little to no input from a human driver in an autonomous vehicle [10, 12]. There has been ongoing work to develop the appropriate vehicle-to-vehicle, and vehicle-to-infrastructure communication capabilities for autonomous vehicles [12]. One essential piece to future autonomous vehicles is Dedicated Short Range Communications (DSRC), which supports communication between vehicles (vehicle-to-vehicle) and also from a vehicle to a communication network of roadside units [12]. DSRC is expected to improve the reliability, safety and

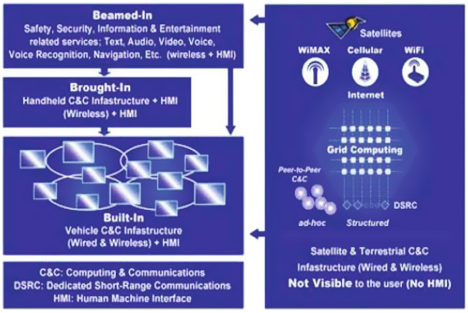

Fig. 6. From [12], illustrates that autonomous vehicles are likely to incorporate beamed in, brought in, DSRC as well as Satellite capabilities in order to support their communication needs.

Fig. 7. Vehicle infrastructure initiative from [12], which is grounded on IEEE 1609.x & IEEE 802.11p standards.

performance of autonomous vehicles [8]. See Fig. 6 from Gharavi et al. below for a mapping of the communication possibilities of automated vehicles.

Figure 7 provides a broader picture of the components and communication channels of the vehicle infrastructure or vehicle-to-infrastructure initiative.

If vehicles are able to communicate with each other via vehicle-to-vehicle and vehicle-to-infrastructure communication capabilities, then they would be able to better inform each other of road conditions and hazardous situations [12]. Vehicle-to-infrastructure communication would support the ecosystem of autonomous vehicles and they will be able to seamlessly communicate with emergency services and help keep the maps up to date with added precision [12]. As noted earlier, vehicle-to-vehicle communication and vehicle-to-infrastructure communication will reduce driver stress and lead to a safer driving environment [10, 12]. Reduced driver stress can eventually lead to a driving environment where humans could focus on other activities in the car and enjoy other things on their trip outside of driving. Researchers working in this space have noted that necessary physical infrastructure changes will be needed to permit autonomous vehicles to communicate seamlessly with the infrastructure and with each other [9, 10, 12].

General Implications on Trucks, Buses and Motor Bikes. Autonomous vehicles are also likely to impact human life for people working directly in the transportation sector. As it was briefly mentioned previously, many working people in the transportation sector will be directly affected by fully autonomous vehicles. In the United States alone, there are over 3 million truck drivers [59]. Fully autonomous vehicles will lead to the elimination of jobs for truck drivers, if a human driver is not required to be present [60]. According to the United States Department of Labor there are almost one million bus and taxi drivers [30, 31], whose jobs will be eliminated once fully autonomous vehicles are available. These implications are clearly not directly focused on human interaction, but the general implication of autonomous vehicles will potentially change or affect the lives of millions of people.

It is important to note here that while this article is focused on human-interaction with autonomous vehicles, the interaction that people have with varying levels of automation in a personal automobile may be very different for motorbikes, buses and trucks. In reference to buses and trucks, this may potentially be an extremely sensitive area from a design and development perspective considering an accident is likely to be more catastrophic due to their large size and weight compared to a personal passenger car. Additionally, a motorbike operates differently from a truck, bus and even passenger cars. These subtle but important differences will need careful consideration in reference to their design and implementation as these autonomous cars, motorbikes, buses and trucks are created.

Trust. Aeberhard et al. suggest that trust is extremely important in reference to situations when human beings interact with automated systems; these systems should work as expected and consistently work well [21]. If the needs and expectations of the driver are not met, this could have extremely negative effects on trust in automated systems and eventually autonomous vehicles [63]. In terms of trust, both too much of it and too little of it can be potentially harmful [22, 58]. Too little trust in the system will leave drivers on edge all the time about the decisions that the car makes and too much trust in the system may cultivate drivers that may delay responding or orienting themselves back to the driving environment when necessary [15, 26–28]. Finding this middle ground between highly but not fully automated is exceedingly challenging as automakers want drivers to utilize highly automated features [24]. Still, they do not want complete disorientation from the driving environment since vehicles are not yet 100% autonomous. Automakers and technology companies developing the autonomous vehicle of tomorrow are likely to be most concerned about the initial trust in the system since this is related to how much profit they will be able to make, their success and overall acceptance. In other words, if people do not trust automation in vehicles then it is unlikely that they will be willing to purchase an autonomous vehicle. Low trust in automation could then lead to a lower adoption rate for autonomous vehicles. Automakers and technology companies would then need to focus their efforts on methods to increase driver trust. Researchers who have done work with trust in automation have identified training to be an essential component of improving user trust [63]. However, too much trust in automation can again lead to overuse or misuse of automated systems [22, 58, 63].

Privacy. As data is stored in an increasing number of locations and on a wide range of devices, privacy is inevitably becoming a growing concern [67, 68]. Drivers may be concerned about the data their autonomous vehicle collects about them and also who has access to their information [9, 67, 68]. A nearly endless list of nefarious activities could occur with the data captured by connected or autonomous vehicles. These activities include but are not limited to providing incorrect information to drivers, limiting the functionality the driver has, having access to all details regarding past, present and future driver routes, acting as a different vehicle or making use of denial-of-service attacks to take down the network [9, 67]. Knowing the driving habits of a driver could be exploited for marketing, law enforcement or surveillance [68]. Particular attention will be needed on the topic of privacy as autonomous vehicles become more and more prevalent. Changes to existing structures or legal requirements may be necessary to allow for the evolving needs of users and/or determine the level of vehicle information that should be disclosed [67].

Security. Security is another salient topic in the autonomous space. The work by Petit and Shladover on cyberattacks is the first known research to explore the vulnerabilities that exist that are specific to automated vehicles [8]. They focused on the potential areas of infiltration for attacks, which were extensive. The vulnerable areas include electronic road signs, machine vision, Global Position System (GPS), in-vehicle devices, acoustic sensor, radar, LIDAR, road, in-vehicle sensors, odometric sensors, electronic devices and maps [8]. Considering that each of these attack surfaces often include subcategories, potential areas of attack are even higher. Unfortunately for the autonomous industry, hackers exposed vulnerabilities in a 2015 Jeep Cherokee by demonstrating their ability to take control of the steering, gas, and brake pedals from a remote location [69]. This vehicle, a level 2 on the NHTSA scale, had only a few automated features. A fully autonomous vehicle includes an even wider array of connectivity features, which potentially opens the door to many more opportunities for hackers. The work done by Petit and Shladover has identified many key areas that affords hackers the opportunity to breach the network of an autonomous vehicle; however, research suggests that much more work is still needed in this area [4, 8].

Pricing. Litman makes it apparent in his 2014 research on predictions relating to autonomous vehicle implementations, that the initial cost of an autonomous vehicle is one of the key challenges to deployment of these vehicles [9]. If the average human being cannot afford an autonomous vehicle, then only affluent people will able to enjoy the use of these vehicles until prices are reduced. This would be contrary to the initial overall goal of autonomous cars being created for a safer driving environment since only the select affluent few would be safer and not the general public [3, 11]. Currently, $30,000 could buy a top selling car in the United States [26]. The LIDAR system, needed for detection alone, costs between $30,000 and $85,000 [51]. This excludes the cost of the vehicle and the many other components needed for detection in an autonomous vehicle [51]. Based on these calculations a consumer would need approximately $60,000 or more in order to purchase an autonomous vehicle. A $60,000 vehicle is likely to be too expensive for most Americans, especially considering the top selling automobiles in the United States range between $16,000 and $27,000 [26]. Vehicles such as a Tesla with advanced autonomous NHTSA Level 2 capabilities where the vehicle can temporarily control the powertrain, brake and steering via the AutoPilot feature is likely to be too expensive for average customers, considering its starting price of around $70,000 [25]. As with many other technologies, prices tend to reduce over time with increased production, however the initial cost may be too high for the average car buyer and there is no guarantee on how soon prices will be reduced. Shchetko also notes that it is unclear when an autonomous vehicle will be affordable enough for the mass car market [51].

Time to Adoption. As noted previously in this paper, automakers and technology companies are aiming to deliver a fully autonomous vehicle by the year 2020 [8]. It is important to note that, according to the technology companies and automobile manufactures working on this technology, the year 2020 is approximately the earliest time that such a vehicle could be delivered to consumers. Considering the plethora of related concerns for autonomous vehicles, many of which are discussed in this paper, it is likely that their deployment could take even longer than predicted. The belief that these vehicles will not hit the marketplace as soon as expected is shared among researchers [70]. It is important not to only consider the time to deployment but also the time when autonomous vehicles will be in mass production, which is one of the major factors reducing the purchasing cost for consumers [51]. If only high-income individuals can afford autonomous vehicles, then the impact will evidently be less meaningful to the average consumer.

2.3 Lack of Focus on User Experience for Autonomous Vehicles

It appears that the engineering of autonomous vehicles is on track, however, the understanding of the interaction between the vehicle's actions and driver reactions seems much more ambiguous [19]. Consequently, there will need to be a significant emphasis on the human element in autonomous vehicles, considering all possible interactions for all levels of automation. Since the DARPA Grand and Urban challenges, there has been considerable amounts of work put into the development of the algorithms, functionality and technologies needed for autonomous vehicles; nevertheless, there has been a lack of focus on the user experience and interaction between the driver and the car [1, 3, 9, 14, 34]. Further, the communication infrastructure and current autonomous vehicle technology needed to allow for performance without driver input is not advanced enough for immediate vehicle deployment [10, 12]. Adequate time and attention will need to be paid to the transition stages to higher levels of autonomy and the back and forth interactions between the driver and a fully autonomous vehicle. This transition of control back and forth between driver and vehicle will have to occur for some time due to unexpected situations that the vehicle will be unable to handle or due to some type of system limitation or failure [13, 18]. A greater focus is needed on the driver interaction experience otherwise autonomous vehicles are likely to have a much longer time to adoption.

3 Human-Interaction and Control in Flight Automated Systems

There has been a significant amount of effort in the design of the modern aircraft from a holistic perspective, especially with regard to the human-machine interaction in the airplane [35, 36]. A failure or issue in the cockpit is likely to result in a catastrophe affecting a large amount of people, therefore designers and developers have made great efforts to minimize possible errors or issues. The human-machine interaction in an aircraft is inherently different from that of an automobile; however, equal importance must be given to this interaction within the context of the automobile similarly to that which is given within the context of airplane development [19]. While it is true that the cockpit of an airplane is more complex than an automobile in terms of functionality, the roadway has a more extensive range of unexpected and complicated scenarios as well as items that could cause a collision [34, 37]. Airplanes follow rather strict Air Traffic Control (ATC) rules and are generally on the lookout for other airplanes [19, 37]. Special instructions also exist when flying low to avoid helicopters and high rising objects [19, 37]. On the roadway, a myriad of potential dangers exist that a driver has to be able to react to at any time such as unexpected behaviors from other drivers, motorbikes, cyclists, pedestrians, animals, potholes, and objects or debris obstructing the forward roadway among many others. These are all salient areas of concern that will need to be accounted for in the design of vehicles with autonomous capabilities. Similar to automation in the vehicle, as previously outlined from NHTSA level 0–4, there are different levels of automation that a pilot can use in an airplane [72]. The pilot can select from and combine different levels of automation.

In aviation, the final control of the automation is dependent on the size of the plane. Automation can override the intentions of the pilot for smaller planes, defined as "hard" automation [19, 74–76]. However, with larger aircrafts, "soft" automation is used, where the intentions of the pilot are not overridden by the automated system [19, 74–76]. The idea behind hard automation is to use technology to prevent or limit human error and therefore will not allow a human operator to override preset limits of the system, even if there is an emergency. Airbus planes (small aircrafts), such as the A320, A330, A340, A380, etc., employ this hard protection system [19]. With this hard protection automation, functions go through two phases if it is originated from a human operator [19]. After the human operator performs an action, the system verifies whether the instructions are within system limits prior to the actual execution of those actions on the aircraft's control surfaces. While with soft automation design, pilots are granted complete authority to override the automated system [74, 76]. Boeing (large) aircrafts use the soft protection system [19, 74, 76]. Intentions from a human operator in the soft protection system are immediately relayed to the aircraft's control surfaces. If automation identifies an issue or concern in this soft protection system, it may issue some type of cautionary alert but it will not stop or nullify the intentions of the pilot. In safety critical scenarios soft automation may provide feedback, which may require the pilot to apply more force than usual, but again the automation will not completely stop the intentions of the pilot [19, 74].

These two approaches of soft and hard automation have both advantages and disadvantages in aviation. Aircraft manufactures have adopted completely opposite approaches in practice. From this perspective, it is therefore not clear which is definitely best for vehicle automation. Even though it has been noted that hard automation may cause more human factors issues, there are concerns that also exist with soft automation. The work by Young et al. suggests that we can learn much from aviation in regards to automation [19, 77]. However, it is not a direct mapping in reference to soft or hard automation being the optimal implementation for autonomous vehicles. Both hard and soft automation have been used in the automotive space. Anti-Lock Braking is an example of hard automation in automobiles and Automatic Cruise Control for soft automation. Hard automation in the driving environment will not allow the driver to interact with or control the automation mechanism, while soft automation will provide the driver the opportunity to have ultimate control. The functional implementation of hard and soft automation in the driving environment is very similar to aviation. Many researchers have noted that the driving environment is more complex and also that there is much more variability in the driving environment than in aviation [34, 39]. Similar to aviation, hard and soft automation, has both advantages and disadvantages in the driving environment. In reference to hard automation in the driving environment, Intelligent Speed Adaptation (ISA), a feature that uses GPS position monitoring and maps of database speed limits has been claimed to be able to reduce all injury accidents by up to 37% [34, 40]. The advantages of such a tool is rather clear as the tool would eliminate speeding. However, a major disadvantage of such a feature is that vehicle imposed speed restrictions [19] could potentially cause accidents (especially where there is only a single lane road for each direction of traffic). It would not make sense to implement ISA in an emergency vehicle, nevertheless for situations where a human is rushing to the hospital in a non-emergency vehicle, ISA could be very problematic. Automatic Cruise Control is a prominent example of soft automation and a key advantage is that manual input from the driver will disengage such a system [19]. The disadvantage of this technology is that prior research has found that many drivers failed to reclaim control of the Automatic Cruise Control system in some emergency situations [80]. Another disadvantage includes reduced awareness of the driving environment, since drivers are much less in sync with the driving tasks when Automatic Cruise Control is active [24]. The fact that both hard and soft automation has both advantages and disadvantages does not help the design and implementation research process for future autonomous systems. Even though soft automation seems promising, an entirely new approach to automation for autonomous vehicles may be warranted. Consequently, all possibilities of interaction with an autonomous vehicle need to be critically examined, as it needs to be safe, while at the same time easy for drivers to use and understand.

Another imperative point to consider is that according to the Federal Aviation Administration (FAA), airline pilots have to go through a minimum of 1500 h of flight training before being eligible to earn a license to fly a commercial aircraft [81]. Obtaining a license to drive in the United States has specific age restrictions based on the state in which the applicant resides, however, most states only require the applicant to pass a vision and written exam as well as a physical driving test [82]. Additionally, the training required for drivers can vary. For example, driver A may practice for one month while driver B may practice for a year prior to taking the driver's test, while all pilots have a minimum of 1500 h of training required to be able to fly and comprehensively understand flight controls [81]. Consequently, it is important that automated systems are easy to use and seamlessly integrated into what the driver expects in the variety of situations that could occur. Confusion in an automobile is likely lead to accidents, fatalities and thus become a barrier to adoption [22, 40, 41].

A potential way to address the human-vehicle interaction issues that may occur with future cars is to create a standardized reporting system similar to what is used in aviation [83]. This would allow drivers to report some of the interaction issues that were not necessarily foreseeable prior to the deployment of those particular autonomous vehicles. This would also help to reduce possible accidents, fatalities and consumer frustration for drivers. This is more centralized as opposed to a breaking news story or report, that notifies the public, technology companies and automotive manufacturers of automated human-interaction issues.

4 Suggestions Going Forward

There has been tremendous growth and progress in the automotive space, especially over the past decade and a half. The DARPA Grand and Urban challenges brought much needed attention to autonomous vehicle research and development, and highlighted many of the potential opportunities [3]. ADAS have also contributed to the continuous advancement in automation as well. Automobiles are not only being built to have lower level autonomous features such as level 2 & 3 NHTSA vehicles, but there is ground-breaking work being done to develop the first level 4 fully autonomous vehicle [4, 5].

While the engineering and functionality of autonomous vehicles have been at the center of attention for research and development, there is still much work needed to address the many challenges in automation for drivers. Future research will need to be focused on all possible areas of human-interaction with these autonomous vehicles. There are specific and salient areas of concern, many of which are delineated in this article, such as approaches to control for automation, TOR, individual differences and distraction, among many other factors. If humans are not able to interact or understand these vehicles appropriately, there may be unfavorable shifts in the overall acceptance and use of autonomous vehicles.

Many challenges are still present for automotive research, especially for the most advanced states of autonomous vehicles. The sensor technology, cameras, algorithms, machine learning and infrastructure are still not at the level of functionality needed for safe and immediate autonomous vehicle deployment [1, 10]. For example, the fully autonomous sensing technologies need to be improved for sensors, LIDAR, cameras, and others [1]. There has not been enough autonomous vehicle driving data for vehicles to predict and assess all possible driving scenarios [10]. The infrastructure is also not currently in place to support vehicle-to-infrastructure and vehicle-to-vehicle communication on all roads [9, 10, 12]. There is much work ahead, not only from a purely Computer Science and Engineering perspective, but also from a Human-Computer Interaction, Human Factors and Design perspective. To date, even though work is being done to achieve this goal, there are no NHSTA level 4 vehicles that exist [27].

5 Summary and Conclusion

Automotive and technology companies clearly have an onerous task ahead, not only to ensure that autonomous vehicles operate appropriately, but also to be able to interact with humans for all driving cases that could potentially occur. Human Factors, HCI and Design researchers have a grand opportunity to explore, research, appropriately design, and test all possible human vehicle interaction scenarios to contribute to the success and potentially increase the likelihood of acceptance for autonomous vehicles.

There are also cultural and regional differences in driving behavior that will need to be accounted for, considering that people drive differently in various parts of the world and even drive on opposite sides of the road in some parts of the world. This paper investigated many of the human vehicle interaction scenarios that will need to be considered in order for autonomous vehicles to be accepted in the marketplace. Consideration was also given to the changes in the legality around driving behavior that will eventually be needed, as well as the necessary infrastructure needed to support these vehicles.

Autonomous vehicles cannot simply replace human drivers [84]. Automation is shifting driving from actively controlling to a state of monitoring; however, research has suggested that human beings are not good at monitoring [34]. Further, humans tend to increase participation in secondary task with an increase in automation and driver assistance systems as discussed in this paper. The area of secondary task involvement by drivers in vehicles with autonomous capabilities will need extensive research moving forward. Research has also suggested that drivers respond more quickly to visual-auditory information requests than they do to requests that are only visual [14, 22]. Alerting systems in vehicles may need to evolve as the levels of vehicle automation has grown and evolved.

Although human interaction with an airplane and other automated systems is not the same as interacting with an autonomous vehicle as outlined in this survey, a plethora of knowledge can be gained from these interactions with other autonomous systems to be used as a guide or reference point. Driver distraction will continue to be a challenge until autonomous vehicles are able to operate without any human input. The amount of secondary devices that can distract the driver has been increasing, considering the myriad of devices that drivers can bring into the vehicle, not to mention the information rich in-vehicle infotainment systems in cars today. A vast amount of additional research will need to be conducted in order to clearly understand the intentions of drivers and how control will be handled in autonomous vehicles, while at the same time taking into account the variations in driver and personality type. Getting the interaction right the first time is even more important considering that people are not familiar with this technology being introduced. There is an exciting journey ahead for the automakers, technology companies, researchers and legislators to create seamless and safe experiences for drivers in order to promote the growth and broader acceptance of autonomous vehicles.

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