



IMPACT OF AUTOMATED VEHICLE TECHNOLOGIES ON DRIVER SKILLS

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Abstract:

This report analyzes the impacts of technological dependence on the driving skills and the ability of an operator to resume operation of the vehicle, in the event of an automated vehicle (AV) failure or limitation. The findings presented in this work are based on the most recent research on the impact of AV technology on drivers, as well as the most influential studies on this topic performed on the last three decades. Drivers that resume manual operation of the vehicle after a period of automated driving perform poorer than drivers continuously operating the vehicle manually. Prolonged use of automation may cause a loss of skills and awareness of the state and processes of the vehicle. These evolutions pose a number of challenges to the automotive industry, to regulatory authorities, and to drivers.

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EXECUTIVE SUMMARY

The evolution towards more automation and connectivity is one of the greatest forces driving the current changes in the automotive industry. In the history of automobiles, technological evolution has always been followed by a parallel evolution in driving skills and human-vehicle interaction. As automobiles become more automated and connected, it is likely that drivers will change their driving behaviors accordingly.

New technologies used in automated vehicles (AV) will augment or perform more of the tasks normally required of human drivers. In the automotive industry, as well as the research and public sphere, it is widely believed that drivers will become dependent to some extent or even over-reliant on the automation. However, drivers may still want to resume manual operation of the vehicle in some occasions. They may also be required to do so, when faced with an event beyond the programming of these technologies or an automation failure. It is therefore vital to study the implications of these situations, because if the system does not perform as the driver anticipates, this may create dangerous situations that would not exist in the absence of the AV feature.

This report analyzes the impacts of technological dependence on driving skills and on the ability of an operator to resume manual operation of the vehicle, in the event of a system failure or limitation. The findings presented in this report are based on the most recent research about the impact of CAV technology on drivers, their performance, and their comprehension of warnings in critical situations. In addition, the CAR team has analyzed insightful research projects on human factors in automation, ergonomics, as well as aviation automation. In order to analyze the impact of automation on driver performance, factors such as trust and reliance, situational awareness, behavior adaptation, and workload were considered.

It is important to note that the overwhelming majority of studies on this topic were completed on driving simulators; only a few tests were performed on test tracks. Even if lab simulations give relatively relevant insights, they do not accurately predict field performance. Future real-life driving tests are therefore crucial in delivering a complete answer to the central questions of this report. In addition, further research on the implications of the use of connected vehicle (CV) applications for driver performance and skills is also needed, as vehicles that will be developed will most likely feature both automated and connected applications.

With the large scale deployment of AV, it is likely that the role of the driver will evolve, as it has in the past in reaction to important technological advances. Drivers will play a lesser role in maneuvering vehicles. In turn, they will focus on supervising the automation systems and monitoring the environment. This evolution entails changes in driver skill sets. Operating all types of AV, except fully self-driving vehicles, will require supervision and selective intervention skills. It will also require an understanding of the capabilities and limitations of automated features. As driving functions become shared between drivers and automated systems, human operators will need to improve their coordination, cooperation and collaboration skills. Most importantly, drivers will need to maintain a constant level of awareness of the performance of the AV and the environment, while, at the same time, performing secondary tasks. Finally, for the partially automated vehicles, drivers will need to master the techniques of transition from automated to manual driving.

For the last 30 years, research has been discussing how drivers' skills and performances change under the influence of new technologies that make vehicles increasingly automated. Although there are many nuances, most researchers agree that, automation will probably be linked to a loss of skill, a loss of awareness of the state and processes of the system, and an increasing difficulty in troubleshooting. Most researchers agree that when people resume manual operation after a period of automated driving their performances are poorer when compared to those of drivers who only used the manual mode. In addition, drivers are slower to recognize critical issues and to react to emergencies, whether they are caused by an automation failure or simply by a limitation of the technology.

During tests about transfer of vehicle operation from automated to manual, drivers had worse lane-keeping ability and poorer steering behavior immediately after resuming manual control. In another test, drivers retaking control during a critical event also had shorter times to contact and shorter minimum headway distances. One noteworthy study found that it took a driver 10-15 seconds to resume manual control, and around 40 seconds to finally reach an adequate and stable control. However, it has been proved that response times also depend on the type of critical event encountered and the type of distraction from secondary tasks.

Research findings show that drivers have shorter response times and better maneuvering performances when they expect to resume manual control, for example in the case of a known automation limitation (e.g. exiting a freeway

to enter a residential area), than when they do not expect the transfer, as is the case for automation failures or other critical events. One test placed the minimum warning period at between 2 and 5 seconds before the event that requires the driver to resume manual control.

Overall, drivers reacted to automation failure with varying success. However, on most occasions, drivers were late in resuming manual control. In one instance, half of the drivers reacted only when the situations were critical (safe distance not maintained), and on another test a third of them collided with the lead car.

Most research seems to indicate that the more complex the automation, the less likely it is that drivers' interventions will be successful in case of a failure. Research findings also indicate that drivers are more likely to resume control after a AV failure if the automation is only in charge of longitudinal control and the steering is the driver's responsibility.

Tests show the strong impact of secondary tasks on supervision and reaction to failures of automation, with the tasks requiring strong interaction showing the most prominent effects. Conversely, driver performance was improved by better feedback of system status.

Potential automation failures, or even just limitations, and the likely loss of driving skills reveal a paradox of automation. Drivers may need to regain manual operation of the vehicle when they are insufficiently prepared, when they expect it the least, and in some of the most dangerous situations.

Experience gained from automation in aviation can be very useful when considering the ability of drivers to respond to failures or limitations of AV technology. This concerns topics such as the sharing of authority, the consequences of over-reliance on technology, and skill degradation.

Automation has had a significant impact on pilot performance in aviation. The main problems relate to degraded manual-flying skills, poor decision-making, and possible erosion of confidence, when automation abruptly malfunctions or disconnects during an emergency. Recent research points out that it is not the loss of manual skills that is most problematic, but that of cognitive ones.

The findings of this report indicate great challenges to come for the automotive industry and the regulatory authorities. Important progress needs to be made for example on human-machine interfaces of AVs, and on training and licensing drivers who will use these new vehicles.



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1 INTRODUCTION

1.1 DEVELOPMENT OF CONNECTED AND AUTOMATED VEHICLES

The auto industry has been envisioning self-driving cars since at least 1939, when General Motors presented its “Futurama” concept at the World’s Fair. This system used a combination of road-embedded magnets and radio communication to guide vehicles without driver control.¹

Automated vehicle technology did not hit the consumer market until decades later and then only in limited applications. The earliest automated vehicle technologies to be widely deployed were conventional cruise control (CCC), electronic speed control (ESC), and anti-lock braking systems (ABS). In recent years, more advanced automated vehicle systems, such as automated park assist, adaptive cruise control (ACC), and automated emergency braking (AEB), have become available in an increasing number of vehicles. The most exciting prospect, however, is the fully automated, self-driving vehicle. It is difficult to predict at this point how and when connected and automated vehicles (CAV) will be available for sale and will finally be adopted, even as increasing numbers of private and public sources publish their projections.

Two distinct conceptions about the role of the automated driving systems coexist. Driving automation can be seen, on the one hand, as a way to *substitute* or, on the other hand, to *augment* the driver’s role. The first of these two opposite conceptions implies that machines are better at driving than humans and should therefore replace humans in the driving role.

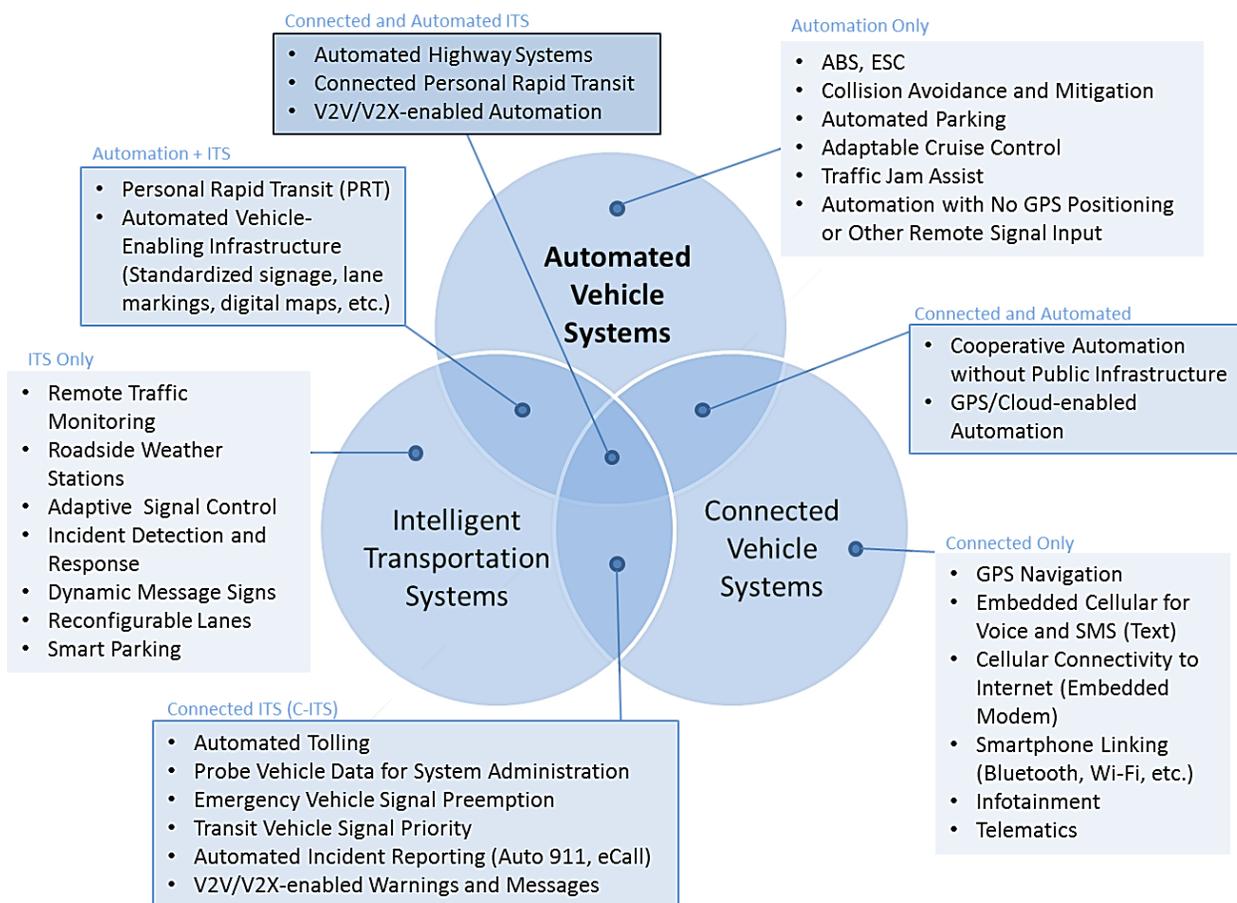
Consequently, there is no need to keep humans in the loop; they can focus on other activities while the vehicle is operating autonomously. The second view is that humans will work more efficiently and effectively if they are provided with powerful and fast tools. Therefore, the goal is to extend or augment human driving capabilities with intelligent machines. In this case, human operators must be informed and involved in the driving task at all times. This conception also implies that humans and automated vehicles must mutually monitor themselves and mutually communicate their intents as copilots.

Nearly all technologies relevant to this report belong to one or more of three general categories: (1) Automated Vehicle Systems, (2) Connected Vehicle

¹ Beiker (2014)

Systems, and (3) Intelligent Transportation Systems. *Automated vehicle systems* improve vehicle performance or driver convenience by automatically controlling vehicle actuation systems. *Connected Vehicle Systems* involve information flow between the vehicle and the world. *Intelligent Transportation Systems (ITS)* refers to intelligent infrastructure and system management. As shown in Figure 1, these systems, alone or in combination, enable valuable products and services.

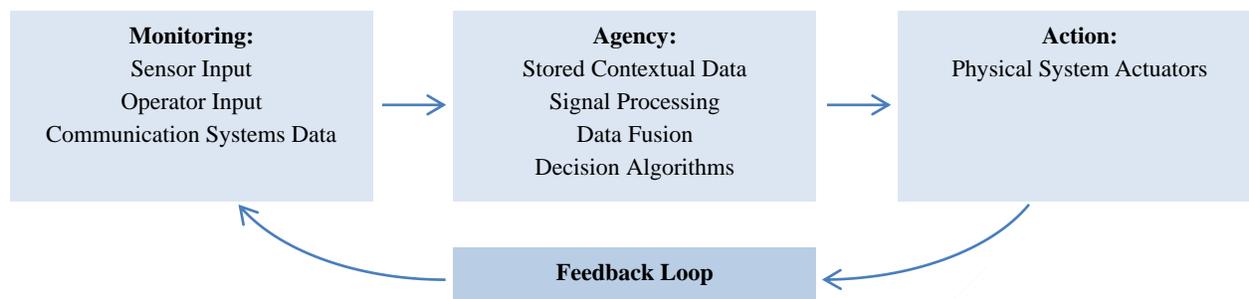
FIGURE 1. TAXONOMY OF ADVANCED TRANSPORTATION AND VEHICLE TECHNOLOGY



For the purpose of this discussion, it is useful to understand the three basic functional components of automation, which are *monitoring*, *agency*, and *action*, as depicted in Figure 2. Monitoring can be viewed as sensing and paying attention, while agency consists of decision-making, and action involves implementing decisions. Furthermore, automated systems that are

considered to be ‘intelligent’ also usually include various feedback loops and possibly even machine learning.

FIGURE 2. GENERALIZED AUTOMATED SYSTEM



A relevant distinction for the current report can be made between *driver assistance systems*, or *advanced driver assistance systems (ADAS)*, on the one hand, and *automated driving systems (ADS)*, on the other hand. ADAS do not assume all the aspects of the dynamic driving task, and thus require a human driver to be actively engaged at all times. ADS control all aspects of the dynamic driving task, implying that ADS-equipped vehicles are self-driving.

Most automated vehicle systems available today are not coupled with connected vehicle or ITS technologies. However, the utility of automated vehicle systems could be improved if such systems were coupled to connected vehicle systems and/or ITS. For example, if two or more vehicles with ACC were able to communicate in real-time via dedicated short-range communication (DSRC), the vehicles could engage in cooperative adaptive cruise control (CACC), or automated platooning. The decrease in following distance allowed by CACC can relieve drivers of many aspects of the dynamic driving task and improve fuel efficiency by as much as 15 percent in certain scenarios.² Researchers are also investigating the potential for CACC to increase highway capacity without expanding the physical infrastructure.³ The USDOT envisions a future transportation system with broad interdependencies between automated and connected vehicle systems with ITS infrastructure.⁴

² Zhang et al. (2014)

³ Cambridge Systematics (2012)

⁴ Barbaresso et al. (2014)

1.2 LEVELS OF VEHICLE AUTOMATION

Various organizations have introduced taxonomies and classifications of automation ‘levels’ to differentiate between systems with various capabilities. Current taxonomies include the following:

- NHTSA Preliminary Statement of Policy⁵
- SAE J3016⁶
- UK Department for Transport (DfT)⁷
- UK Parliamentary Office of Science and Technology (POST)⁸
- German Highway Research Institute (BASt)⁹

TABLE 1. NHTSA LEVELS OF AUTOMATION¹⁰

Designation	Description
Level 1 – Function-specific Automation	<p>One or more specific of the control functions are automated. If multiple functions are automated, they operate independently of each other. The driver has overall control and is solely responsible for safe operation. The driver can choose to cede limited authority over a primary control, the vehicle can automatically assume limited authority over a primary control, or the automated system can aid the driver in certain normal driving or crash-imminent situations. The automation system does not replace driver vigilance and does not assume driving responsibility from the driver.</p> <p>E.g.: conventional cruise control (CCC) and adaptive cruise control (ACC), electronic stability control (ESC), dynamic brake support, and lane keeping.</p>
Level 2 – Combined Function Automation	<p>At least two primary control functions are automated and work in unison to relieve the driver of control of those functions. Driver and vehicle have shared authority in certain limited driving situations. The driver is responsible for monitoring the roadway and operating the vehicle. The driver is expected to be available for control at all times and on short notice. The system can relinquish control at any time with no advance warning. The distinction between Level 1 and Level 2 is that the driver may operate the vehicle without their hands on the wheel and foot off the pedal at the same time.</p> <p>E.g.: adaptive cruise control in combination with lane centering.</p>

⁵ NHTSA (2013)

⁶ SAE International (2014)

⁷ DfT (2015)

⁸ POST (2013)

⁹ BASt (2012)

¹⁰ Descriptions are near-direct quotes from the NHTSA Statement but may be edited for brevity, clarity, and emphasis.

Level 3 – Limited Self-Driving Automation

Vehicles at this level of automation enable the driver to cede full control of all safety-critical functions under certain traffic conditions. In automated mode, the driver may rely heavily on the automated driving system (ADS) to monitor for changes in the driving environment that would require transition back to driver control. The ADS is expected to alert the driver that they must reengage in the driving task with sufficiently comfortable transition time (i.e., an appropriate amount of transition time to safely regain manual control). The driver is not expected to constantly monitor the roadway while driving.

E.g.: a self-driving car that can determine when the ADS is no longer able to function, such as when approaching a construction zone.

Level 4 – Full Self-Driving Automation

The ADS is designed to perform all safety-critical functions and monitor roadway conditions for an entire trip. The driver is not expected to be available for control at any time during the trip. Safe operation rests solely on the ADS. This includes both occupied and unoccupied vehicles.

In the United States, the levels introduced by NHTSA in the Preliminary Statement of Policy and by SAE International are of particular importance. While the NHTSA classification is preliminary and does not have the force of law, it is important because it reflects NHTSA’s potential approach to automated vehicles if/when the agency adopts formal regulations. NHTSA’s levels of automation have become largely adopted by industry stakeholders as the de facto measurement of automated vehicle capability in the US.

TABLE 2. NHTSA VS. SAE LEVELS OF AUTOMATION

	NHTSA Level	SAE Level
Advanced driver assistance systems (ADAS)	Level 1 – Function-specific Automation	Level 1 – Driver Assistance
	Level 2 – Combined Function Automation	Level 2 – Partial Automation
Automated Driving Systems (ADS)¹¹	Level 3 – Limited Self-Driving Automation	Level 3 – Conditional Automation
	Level 4 – Full Self-Driving Automation	Level 4 – High Automation
	Level 5 – Full Automation	Level 5 – Full Automation

¹¹ Many sources represent NHTSA and SAE levels two and three as being equivalently bounded. However, SAE has distinguished level 4 from level three by way of an ability to achieve a *minimal risk condition* if the vehicle encounters conditions that require action from the human driver, and the human driver is unresponsive. Thus, an example of an automated vehicle that would be classified an NHTSA level three, but SEA level 4 would include a highway pilot feature that is able to transition to a minimal risk state if the human driver fails to resume the dynamic driving task when requested to do so.

For consistency, this report uses only the NHTSA taxonomy in its analysis. The NHTSA levels of automation are more relevant for they discussion, as they focus more on driver interaction with automation.

Parallel to these levels of automation control, there is a more important question concerning the level of authority assigned to the automation. This relates to where lies the ultimate authority (or the power of veto) over the vehicles actions, with the human operator (soft automation) or with the technology (hard automation). Hard automation employs technology to prevent human error, has ultimate authority on the vehicle and can override the human operator’s inputs. Soft automation on the other hand can be overridden by drivers if they want or need to.

TABLE 3. HARD AND SOFT AUTOMATION TECHNOLOGIES¹²

Hard automation	Soft automation
Automatic transmission	Cruise control
Anti-lock braking system (ABS)	Adaptive cruise control (ACC)
Traction control	Automated steering (AS)
Electronic stability control (ESC)	Collision waning system (CWS)
Collision avoidance system (CAS)	Parking aids

Some of these technologies already have been implemented. Level 1 driver assistance systems can be as simple as ABS, ESC, and ACC. Several automakers have introduced automated driving systems (e.g., traffic-jam-assist) that meet the requirements of NHTSA Level 2 automation.

A few manufacturers have introduced systems that appear to straddle the line between Levels 2 and 3. Vehicles at this level of automation enable the driver to cede full operation of all safety-critical functions under certain traffic or environmental conditions, and in those conditions to rely heavily on the vehicle to monitor the driving environment. This would suggest Level 3 status, but these systems are not generally identified as Level 3 automation because the driver is expected to actively observe the system and remain vigilant for situations that require re-engagement with the physical aspects of the dynamic driving task with minimal warning. It seems only a matter of degree of reliability that distinguishes Levels 2 from 3 in this case.

¹² Young et al. (2007)

The Google prototype self-driving car is likely the most advanced of these projects. Google's self-driving car has been prepared to navigate every street in Mountain View, CA, and may soon be made available in beta-version to select non-test-drivers for use, such as typical Google employees. However, none of the vehicles currently for sale would allow a person to safely and reasonably "let the car drive". Automated low-speed shuttles have been deployed in a few locations, but only in very limited pilot projects.

1.3 ROLE OF HUMAN OPERATORS: CURRENT HYPOTHESES ON ITS EVOLUTION

Vehicles from the first half of the twentieth century are still capable of operating on modern highways in mixed traffic. Most cars still have four wheels, a steering wheel, a gas pedal, and a brake pedal.

However, gradual changes in vehicle technology, consumer trends, and societal transformations have resulted in a different driving experience. Over time, the role of human operators of motor vehicles has evolved. For examples, nowadays, the human operators need to act less as *mechanics*, as they did in the early days of motor vehicles, and may concentrate primarily on their driving role.

If AV technologies are broadly and successfully adopted, the drivers' role will evolve further (see Figure 3). Researchers and manufacturers alike agree that these new technologies will make drivers' focus much more on supervising the automation systems¹³ and monitoring the environment. Drivers will be increasingly taking on roles of management of the various automated systems and information flows in and out of the vehicle. Consequently, the human operator will play a lesser role in maneuvering AVs. In other words, the primary task will no longer be active control, but supervisory control¹⁴, especially for partially automated vehicles (NHTSA levels 1 to 3).

However, that does not necessarily imply that the indirect control as a supervisor will be less demanding than manual control. Members of the research community and automotive industry have doubts that people will be

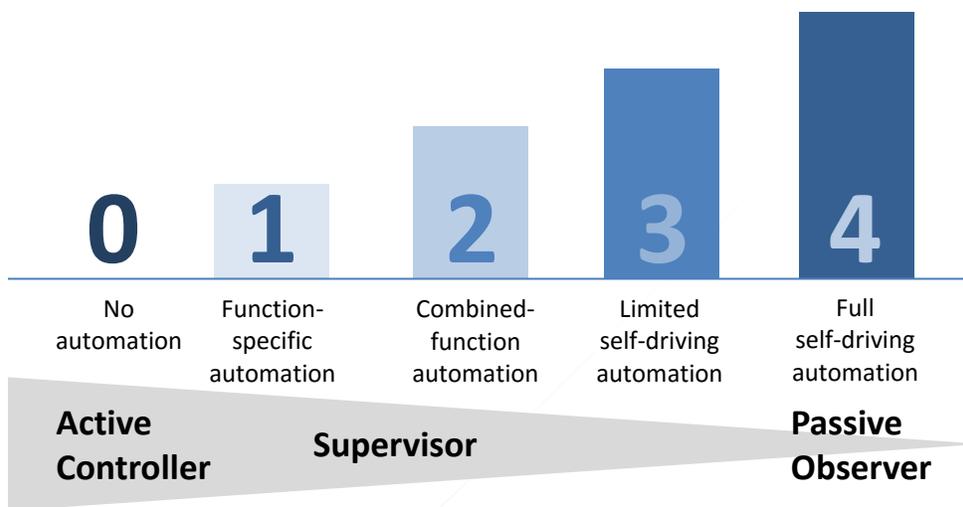
¹³ Bainbridge (1983)

¹⁴ Sheridan (2002)

suited for this tedious monitoring role of constantly watching to detect and correct technology failures.

Finally, when talking specifically about fully autonomous vehicles (NHTSA level 4), humans are likely to have a passive observer role, as they will not be required to provide any input into the driving task.

FIGURE 3. EVOLUTION OF THE ROLE OF THE HUMAN OPERATOR IN THE DRIVING TASK



1.4 RESEARCH QUESTIONS AND METHOD

Much uncertainty exists about the impact of the deployment and adoption of AV both at the societal and individual level. While the development of some AV technologies is relatively advanced, in-depth human factors research is still needed to better understand the interaction between the drivers and the new AV features.

Over the past 30 years, human factors research related to driving automation has focused on several topics:

- Drivers’ willingness to use the automation;
- Drivers’ support with the appropriate level of automation;
- Transitions between manual and higher levels of automated driving;
- Possible loss of skill;
- Drivers’ reactions to errors of AV technology.

One of the most important hypotheses is that, as CAV features augment or perform more of the tasks normally required of human drivers, it is likely that

vehicle operators will become dependent or at least over-reliant on the technology. In this sense, one of the greatest challenges for the large scale deployment of CAV is the process of transferring the driving responsibility between the human driver and the vehicle.

This leads to another key issue: if the sensors and/or the connected/automated responses fail mechanically or are faced with a situation beyond their programming, the operator may be required to resume control, at least in the vehicles that will maintain manual driving features.

RESEARCH QUESTIONS AND SCOPE

This report analyzes the impacts of technological dependence on driving skills and the ability of an operator to resume control of the vehicle, in the event of a CAV technology failure or limitation.

Four questions will guide the analysis:

- **Are drivers likely to become dependent on AV technologies?**
- **What are the manifestations of drivers' dependence on driving automation?**
- **What is the impact of this dependence on drivers' skills?**
- **Are drivers capable of resuming manual operation of a vehicle, for example when faced with a system failure or a situation beyond the programming of CAV technologies?**

The report will focus mainly on NTHSA automation levels 1 to 3, since they involve different degrees of shared authority between the human operator and the automation. The discussion applies to fully automated vehicles (level 4) only to a limited extent. For level 4 vehicles that will be designed to be operated solely in automated mode and that will lack a manual control option, driving skills will likely not be necessary.

Although it is not the focus of the analysis, this report also covers the effects of connected vehicle technology (V2V and V2I applications) on driver skills and performance. It is important not to treat the impacts of automation and connectivity completely separately, because it is highly likely vehicles will have both types of applications increasingly.

In studying the impact of technological dependence on driving skills, factors like driver age and experience will also to be investigated. Concerning drivers' ability to retake manual control and to react to failures or limitations

of these new technologies, it is important to consider the type and distribution of these events.

METHOD

The current report is based mainly on the most recent research on the impact of AV technology on drivers, as well as the most influential studies on this topic performed in the last three decades. In addition, the CAR team has analyzed insightful findings from research on human factors in automation, ergonomics, as well as aviation and rail automation.

The overwhelming majority of studies on this topic have been completed on driving simulators, with only a few performed on test tracks. Most of these studies used between 25 and 50 participants (male and female, younger and older drivers, experienced or unexperienced with AV technology).

LIMITS OF THE RESEARCH

Even if results from real-life driving tests do not exist for the moment, the current research gives a relatively relevant insight on the impact that AV technology will have on driver skills. Most of the research findings were coherent; however, test parameters were quite diverse. Therefore, the results shed light on a great number of aspects linked to the human reactions to automation failure and limitation. Nevertheless, more tests are required to verify some of these initial results.

Driving simulator data may not apply with great accuracy to the real behavior of drivers, for a number of reasons. It is expected, for example, that trust in automation, and therefore engagement in secondary tasks, will be lower in real driving situations. In addition, in real-life conditions, the consequences of not reacting to an automation failure or limitation are much greater than in a simulator, which might compel drivers to be more vigilant on the road.

Strictly speaking about connected vehicles, research on the impact of CV applications on driver performance and skills is quite limited. Few research efforts have concentrated on the effects that connectivity features (e.g., navigation systems, V2V, V2X) have on driver skills. The full implications of the real-life use of CV applications are yet to be fully understood.

More driving experiments using real CAV technology on actual roads or test tracks are necessary in order to verify whether the results obtained on driving simulators are sufficiently relevant for road driving conditions. Automakers

like Volvo¹⁵ and GM¹⁶ have recently announced that they will begin testing autonomous driving technologies in real-life conditions, which will certainly generate much needed data on the naturalistic use of these features.

Most of the research analyzed in the scope of this report concerns technologies belonging to NHTSA Levels 1 and 2 of automation (e.g., adaptable cruise-control, traffic-jam assist). As new technologies are being developed, it is important to also test the impact of higher levels of automation and connectivity on driver performance.

Finally, it is important to pursue research with more subjective inputs as the self-perceived skill evolution of drivers that use CAV technologies, attitudes and behaviors linked to these features. This type of information would contribute to understanding the medium to long-term impact of these different technologies.

1.5 PLAN OF THE REPORT

The second chapter gives a brief overview of AV technologies that need to be considered in the scope of this report, and some of their limitations and potential failures.

Chapter 3 mentions the most important evolutions in the skills required for operating a AV and reacting to an automation failure.

Chapter 4 discusses the impact of CAV technology on driving skills by analyzing the changes in human factors, such as trust and reliance, situational awareness, and workload.

¹⁵ At the end of 2013, Volvo has announced its Drive Me project, that will make 100 self-driving XC90 Volvos available to consumers around Gothenburg for use in everyday driving conditions. The cars will be driven autonomously on about 50 kilometers (31 miles) of selected roads. Among the features that will be tested is the IntelliSafe Auto Pilot, an interface that will allow drivers to activate and deactivate the autonomous mode through specially-designed paddles on the steering wheel. The interface was developed to oversee how drivers will transition between manual and automated control.

Source: <https://www.media.volvocars.com/global/en-gb/media/pressreleases/136182/volvo-car-group-initiates-world-unique-swedish-pilot-project-with-self-driving-cars-on-public-roads>

¹⁶ In October 2015, GM announced that a fleet of 2017 Chevrolet Volts designed to drive autonomously will be tested at the Warren Technical Center campus late in 2016. The vehicles will be available to GM employees through a car-sharing app.

Source: http://www.gm.com/article.content_pages_news_us_en_2015_oct_1001-gbc.html

The most relevant research results on the human capacity to react to failures and limitations of CAV technologies are discussed in the fifth chapter. Findings highlight that differences in performance depend on the level of automation, and on whether the transfer to manual operation of the vehicle was expected by the driver. Based on these findings, the implications of driver performances are examined in the final part of this chapter.

The fifth chapter discusses some of the most noteworthy findings related to the implications of connected vehicle applications for driver performance and skills.

Lastly, chapter 7 brings interesting insights from the rail and aviation automation that are relevant for the current discussion on the deployment of AVs.

The conclusions take further the implications of the impact of AV technologies on driver skills. This part mentions a few challenges that these evolutions pose to the automotive industry, to regulatory authorities and to drivers in general.

2 CONNECTED AND AUTOMATED VEHICLE TECHNOLOGIES

As stated in the introduction, a great variety of CAV technologies is being developed and some of these features are already in use.

For the purpose of this report, it is important to understand the interactions between the driver and the technologies and especially the situations in which these features activate. Table 3 presents a brief description of the latter aspect, for some of the most important AV technologies. An understanding of the activation methods of these features is useful for grasping how a driver would react upon resuming manual control of the vehicle.

TABLE 4. NHTSA AND SAE AUTOMATION TAXONOMIES AND ACTIVATION METHODS

NHTSA Level	SAE Level	Automated System	Activation Methods Longitudinal (drivetrain, braking), Latitudinal (steering)
Level 1 Function-specific Automation	Level 1 Driver Assistance	Antilock Brakes (ABS)	Automated system activates brake modulator unit when driver initiates hard braking that would otherwise result in wheel-lock.
		Electronic Stability Control (ESC)	Automated system activates brakes, and possibly drivetrain (throttle-down), when system perceives that driver’s actions would otherwise result in lateral wheel-slip.
		Autonomous Emergency Braking (AEB)	Automated system activates brakes, and possibly drivetrain (throttle-down), when the system perceives that a crash is imminent.
		Lane Keep Assist	Automated system activates brakes, and possibly steering, when system perceives that the driver has failed to maintain the vehicle within a lane.
		Adaptable Cruise-Control (ACC).	Driver activates automated system to maintain a set distance from a lead vehicle or a set speed if there is no lead vehicle. Automated system executes longitudinal (drivetrain, braking) portions of dynamic driving task.
		Automated Parking Assistance	Driver activates automated system to activate steering control to guide the vehicle into a spot designated by the driver. For Level 1 systems, human driver must execute longitudinal portion of the dynamic driving task.
Level 2 Combined Function Automation	Level 2 Partial Automation	ACC with Lane-centering	Human driver activates system. Automated system controls all three activation methods (brake, drivetrain, and steering). Human driver must monitor driving environment and vigilantly supervise automated execution of dynamic driving task.
		Traffic-Jam Assist (TJA)	
		Automated Parking	

		Automated Integrated Emergency Response	Automated system controls all three activation methods (brake, drivetrain, and steering) when the system perceives that an emergency maneuver is necessary to avoid a crash. Human driver must assume dynamic driving task following automated emergency maneuver.
Level 3 Limited Self-Driving Automation	Level 3 Conditional Automation	Conditional Automation	Human driver activates automated driving system when conditions are appropriate. Automated system is designed to execute all functions of dynamic driving task within a specific driving environment. Human driver must assume dynamic driving task following reasonable warning time.
	Level 4 High Automation	Hypothetical “Highway Autopilot” Feature	Human driver activates automated driving system when conditions are appropriate. Automated system is designed to execute all functions of dynamic driving task within a specific driving environment. Human driver should assume dynamic driving task following reasonable warning time. <i>Transitions to minimal risk condition if driver does not take over.</i> ¹⁷
Level 4 Full Self-Driving Automation		Google Self-Driving Vehicle Prototype	Automated driving system executes entire dynamic driving task and is capable of doing so for an entire trip. Human driver should assume dynamic driving task following reasonable warning time. ¹⁸
		Driverless shuttle	Automated driving system is capable of performing the complete dynamic driving task while following a pre-defined route within a confined geographical area, such as a campus shuttle. ¹⁹
	Level 5 Full Automation	No known example	Automated driving system executes entire dynamic driving task and (per SAE J3016) is “characterized by trip-level and geographically unconstrained on-road automated driving (i.e., an automated vehicle capable of all on-road driving – without geographical or modal limitation – that can be legally performed by a human driver).”

Several manufacturers are working on these technologies and for the moment, their solutions are quite diverse. For instance, there are no standard Forward Collision Warning (FCW) parameters such as gap setting, type of warning display or modality (visual, haptic, or auditory).

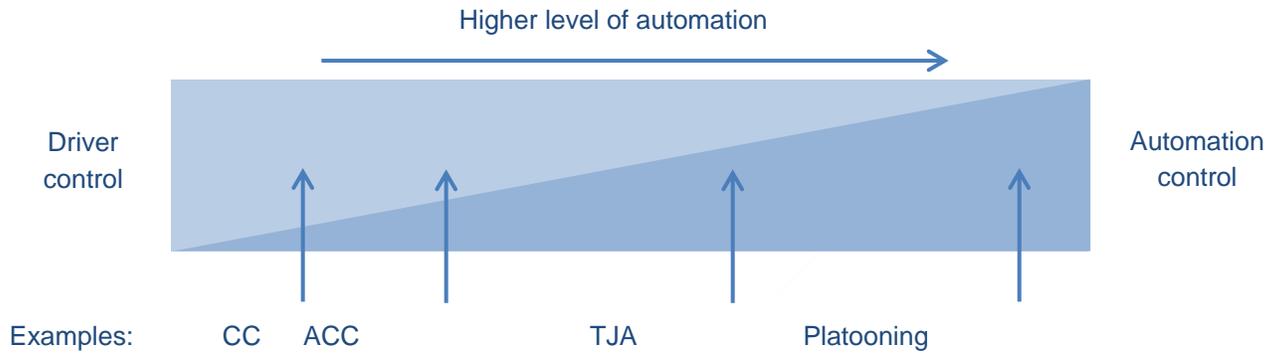
¹⁷ Transition to “minimal risk condition” (e.g., pulling to the shoulder or carpool lot) is a key distinction between SAE Level 4 and Level 3. Highway pilot does not qualify as NHTSA Level 4 because it is not capable of completing a trip in automated mode.

¹⁸ Functionality may require high-precision 3D digital map. Neither NHTSA (Level 4) or SAE (Level 4) definitions require vehicles to operate in all potential conditions (e.g., the operation of such a vehicle may be limited by conditions such as weather or geographical boundaries). Thus, the Google Prototype Self-Driving Car meets NHTSA Level 4 requirements despite being limited by speed and geography.

¹⁹ Neither NHTSA (Level 4) nor SAE (Level 4) definitions require vehicles to operate in all potential conditions (e.g., the operation of such a vehicle may be limited by conditions such as weather or geographical boundaries).

The distribution of responsibility between the driver and the automated driving system changes with the increase of the level of automation, as illustrated in Figure 4. As shown in chapter 5, this distribution of responsibility has an important effect on the ability of drivers to resume manual control of the vehicle.

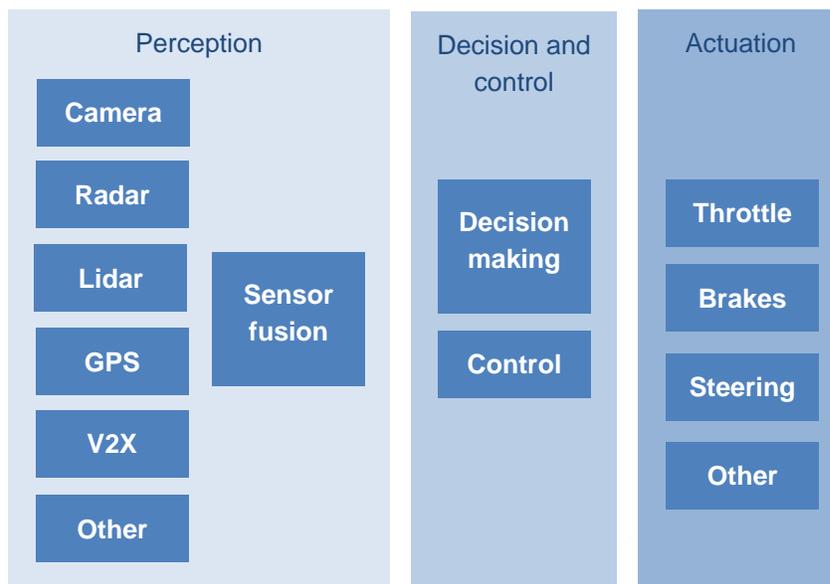
FIGURE 4. SPECTRUM OF AUTOMATION DEGREE BETWEEN DRIVER AND AUTOMATION CONTROL²⁰



A complete overview of all potential limitations and failures of the aforementioned AV technologies is beyond the scope of this report. An extensive failure mode and effects analysis (FMEA) of the AV features described in Table 3 would be needed for a complete reliability study. A FMEA involves reviewing as many components, assemblies, and subsystems as possible to identify failure modes, and their causes and effects. This would then allow for an extensive analysis of drivers’ reactions and performances for each type of failure. For the purpose of this report, we have assumed that, hypothetically, any part of a automated driving system (as schematically described in Figure 5) could be susceptible to failure.

²⁰ Nilsson (2014)

FIGURE 5. LOGICAL ARCHITECTURE OF VEHICLE AUTOMATION WITH EXAMPLES OF COMPONENTS²¹



For the purpose of this report, failures of automation levels 1 to 3 are divided into three general categories:

- Errors: the automation activates when it is not required;
- Misses: automation fails to activate;
- Partial misses: automation does not fully activate.

For example, several research projects mentioned in chapter 5 studied different types of ACC failures: unwanted acceleration, complete lack of deceleration, partial lack of deceleration, speed limit violation.

FCW systems also have, for the time being, potential failures. In picking up target objects, FCW features are limited by the capacities of their radar system. For example, the radar may select static roadside objects by mistake or, especially on a curved road, a target in an adjacent lane may be chosen as the lead vehicle. By mistaking another target as the lead vehicle, a FCW is likely to provide false alarms.

²¹ Nilsson (2014)

3 SKILL SET REQUIRED FOR USING AUTOMATED VEHICLE TECHNOLOGIES

A typical modern driver undoubtedly has a unique skill set compared to a driver from previous decades. While many of today's drivers have never mastered a manual transmission, or have never been required to pump the brakes on a slippery road, they are beginning to utilize modern CAV features such as adaptive cruise control or blind spot warning lights, as well as touch-screen interfaces for infotainment functions and hands-free calling. The steady integration of these AV technologies into modern vehicles will continue to influence the skill set required to safely operate in traffic.

3.1 SKILLS NEEDED TO MONITOR THE NORMAL FUNCTIONING OF AUTOMATED DRIVING SYSTEMS

Advanced AV technologies that will potentially see deployment in the coming years and decades could imply the need for a drastically different set of driving skills than the one needed for today's vehicles.

Driving AVs will require better supervision and selective intervention skills, rather than manual control and maneuvering skills. The supervision role, especially for NHTSA automation levels 2 and 3, will require skills in terms of coordination (sharing information), cooperation (being aware of and supporting each other's goals), and collaboration (working on a shared project).²²

Additionally, drivers will need to adapt to the different levels of automation and to understand the distribution of tasks between automation and manual control for each level. In other words, familiarity with the electronic functions of AVs will be required for all drivers using automation levels 1 to 3. Furthermore, operators will need to know when and how to interact with automated driving systems.

In-depth analyses have shown that, from a human factors perspective, each of the automation levels 1, 2, and 3 require different skills from drivers, especially in terms of situational awareness. For example, highly automated

²² James (2014)

driving (HAD), NHTSA Level 3 automation, on the one hand, and ACC driving (Level 1), on the other hand, require different types of interaction between the vehicle and the human operator.²³ Namely, in a highly automated car, the driver has the possibility to perform complex secondary tasks, a feature that is seen as one of the biggest advantages of HAD, whereas in an ACC equipped car, the driver must attend to the roadway constantly. Therefore, the gradual deployment of automation will put more emphasis on progressive and continuous training, rather than the current, one-off, initial training.

On a more general note, drivers will need to develop the capacity to maintain a constant level of awareness of the performance of the AV and the environment, while, at the same time, performing secondary tasks with a variety of difficulty and attention requirements. Overall, operators should also know when it is safe to engage in secondary tasks. Namely for NHTSA level 3 vehicles, drivers must develop the ability to resume manual operation of the vehicle in a timely manner when the system requires it, as they are not required to constantly monitor the roadway. Therefore, drivers will need to master the techniques to transition from automation to manual control, as well as between different levels of automation.

One potential difficulty is that, for the moment, the AV technologies currently developed are more heterogeneous than contemporary non-automated motor vehicles. Acquiring the skills and knowledge necessary for each type of automation might prove to be a more demanding task compared to manual-control vehicles.

3.2 SKILLS NEEDED TO RESPOND TO FAILURES OR LIMITATIONS OF AUTOMATED DRIVING SYSTEMS

Operators' supervisory role will require them to maintain a certain level of vigilance even though their task is to monitor automation, rather than to operate the system manually. Thus, in the case of failures of the ADS, human operators must go from being passive monitors to active drivers. The drivers will therefore act as a backup for automation, which requires a swift response

²³ De Winter (2014)

in critical or dangerous situations. This applies for vehicles equipped with Levels 1, 2, and, to a limited extent, 3 ADS.

Firstly, drivers may need to be fully aware of the correct functioning of ADS features, in order to be able to recognize automation errors. As long as shared authority between the human operator and the automation is required to some extent (for vehicles belonging to NHTSA levels 1 to 3), the driver must fully understand the capabilities and limitations of the ADS and be aware of what the system is doing and when intervention might be needed.²⁴ Failure to do so may become a leading cause of crashes, both automation- and human-induced.

Drivers' beliefs and expectations about how AV technology is supposed to work determines the manner in which they will interact with the system. This is important because in some circumstances, the operators' understanding of how a system should behave does not match objective reality. This creates a situation that can lead to an unpleasant or unsafe surprise for the user, also called mode confusion, when the operator is uncertain about the status or behavior of the automation.²⁵ Therefore, in order to avoid mode confusion, drivers must have an accurate understanding of the normal functioning, limitations and potential failures of the ADS, as stated earlier²⁶.

Secondly, operators will need to maintain a level of alertness sufficient to be able to identify and ADS failure and react to them as fast as possible. Moreover, when faced with an automation failure, the drivers must know up to what point it is appropriate to take over the vehicle and how to do so successfully.²⁷ In order to know how to react when faced with a limitation or malfunction, drivers must therefore maintain a skill level allowing them to manually perform all tasks that are normally done by automation (e.g., longitudinal control, lateral control), as well as emergency maneuvers (e.g., crash avoidance).

²⁴ Cummings and Ryan (2014)

²⁵ Brederke and Lankenau (2005)

²⁶ A relevant example of mode confusion is a crash involving Tesla Models S in May 2016. The autopilot system didn't engage when the driver assumed it would to prevent them from rear-ending the preceding vehicle. To this, Tesla responded with data showing the driver had tapped the brake pedal before the crash, deactivating autopilot features. This situation shows that the driver did not fully understand the consequences of tapping the brake pedal (i.e. fully deactivating the Tesla autopilot system, including the automatic emergency braking) and was then confused as to what automated features were still activated.

Reported in Fortune, May 14, 2016: <http://fortune.com/2016/05/14/tesla-autopilot-crashes/>

²⁷ Toffetti et.al. (2009)

Given the highly probable loss of skill brought on by ADS, the paradox of automation becomes apparent. Thus, drivers will need to retake manual control of the vehicle when they expect it the least and in some of the most dangerous situations.²⁸

²⁸ Bainbridge (1983)

4 IMPACT OF AUTOMATED VEHICLE TECHNOLOGIES ON DRIVING SKILLS

In recent years, a great number of research teams have focused on understanding the significance of human factors for AV, specifically the impact of this technology on driving behavior, skills, and abilities.

Some of the most important human factors to take into consideration for the deployment of AV are trust and reliance, situational awareness, behavior adaptation, and workload. In addition, this chapter will also discuss the impact of ADS on driving maneuvering skills.

Researchers have identified several issues with human operators' use of automated vehicle features. Soft driving automation systems, which can be overridden by drivers, are particularly associated with problems caused by reduced driver mental workload (performance problems when the driver needed to reclaim control). Hard automation applications, which have ultimate authority on the vehicle and can override the driver's inputs, on the other hand are associated with problems of trust, situational awareness and mental models. Finally, issues linked to behavioral adaptation have been linked to both soft and hard automation systems.²⁹

²⁹ Young et al. (2007)

TABLE 5. SUMMARY OF HUMAN FACTORS LINKED TO A SELECTION OF AV TECHNOLOGIES

Human Factors Issue	Systems			
	Forward Collision Warning (FCW)	Adaptive Cruise Control (ACC)	Lane Departure (LD)	Cooperative Adaptive Cruise Control (CAAC)
Willingness to Utilize	Drivers are willing to utilize. However, they need to understand system functioning. The ability to set a customized gap or following distance would be desirable. ³⁰	Drivers are willing to utilize, especially in congested traffic (if the system is programmed for slow speeds). ³¹	Drivers are willing to utilize. ³²	Drivers are willing to utilize and appear to accept the time gaps and following distances. Drivers are more reluctant to use the system, though perhaps not at high speeds. ³³
Trust	Extended exposure (and knowledge of the system) leads to increased trust. Distrust of the system primarily a result of false positives. ³⁴	Trust is dependent on experience with the system and knowledge of the system’s operation. ³⁵ An inaccurate internal representation of ACC may cause the drivers to excessively trust the system. ³⁶	Trust depends on road type (i.e., the system can be less reliable on rural roads where edge lines may not be conspicuous). ³⁷ Drivers tend to learn relatively quickly when and where the system will work.	Trust is dependent on system reliability. ³⁸
Reliance	Extended exposure can lead to over-reliance on the system. ³⁹	Drivers may have an inaccurate mental model of ACC, which may lead to inaccurate expectations of ACC performances and over-reliance on the device. ⁴⁰	Reliance on the system is very limited. ⁴¹	Reliance on the system may occur with extended use. ⁴²
Carryover Effects	Carryover effects could emerge,	Possible carryover effects with	A moderate amount detected (drivers used their turn signals more frequently after	Behavioral adaptation to CACC time gaps may result in shorter gaps during manual

³⁰ Jamson et al. (2008)

³¹ Rosenfeld et al. (2015) ; Seungwuk et al. (2009).

³² Stanton et al. (2011)

³³ Jones (2013); Hoedemaeker and Brookhuis (1998); Levitan et al. (1998); He et al. (2011)

³⁴ Genya et Richardson (2006)

³⁵ Larsson (2012)

³⁶ Rajaonah et al. (2006)

³⁷ Guo et al. (2010)

³⁸ Jones (2013); Lee and See (2004); Parasuraman and Riley (1997)

³⁹ Aust et al. (2013)

⁴⁰ Boer and Hoedemaeker (1998); Goodrich and Boer (2003)

⁴¹ Guo et al. (2010)

⁴² Jones (2013); Lee and See (2004); Parasuraman and Riley (1997)

Human Factors Issue	Systems			
	Forward Collision Warning (FCW)	Adaptive Cruise Control (ACC)	Lane Departure (LD)	Cooperative Adaptive Cruise Control (CAAC)
	similarly to other technologies. ⁴³	conventional cruise control. ⁴⁴	exposure to the system. ⁴⁵	control, which may be a safety risk. ⁴⁶
Distraction	Drivers can become distracted. This depends on the HMI (i.e., if the interface is visual and located below the windshield). Reliance on the system can lead drivers to engage in secondary tasks. ⁴⁷	Over-reliance can lead to distraction since the system (especially those with auto-braking) performs the maneuvers. Therefore, drivers are more likely to be engaged in secondary behaviors. ⁴⁸	Can lead to minor distraction. On certain roads, drivers may use the system to warn them of a lane departure while they are engaged in a secondary task. ⁴⁹	The increased automation of CAAC over ACC may lead to greater distraction. ⁵⁰
Situational Awareness	Related to distraction. If drivers overly rely on the system, they may lose situational awareness (and may not be ready to intervene in a critical situation). ⁵¹	Situational awareness (linked to distraction and over-reliance) can decrease, which makes drivers to be unprepared to intervene in a critical situation. ⁵²	Situational awareness can increase, due to the LD alerts. ⁵³ In addition, older drivers tend to have faster reaction times due to greater situational awareness. ⁵⁴	Reduced workload from CACC use may enable drivers to engage in non-driving-related tasks possibly leading to risks during system failures and emergencies. ⁵⁵
Workload	System use can lead to a decrease in workload if drivers rely on the system to warn them of events. ⁵⁶	Can drastically reduce workload (when compared to driving without the system), especially in congestion. ⁵⁷	Appears low. ⁵⁸	Possible decrease in workload which can lead to performance decrements due to “mind wandering”. ⁵⁹

⁴³ CAR analysis. No specific scientific reports have been found.

⁴⁴ Lasson (2012)

⁴⁵ LeBlanc et al. (2006) ; Ton (2015)

⁴⁶ Jones (2013); Levitan et al. (1998)

⁴⁷ Muhrer et al. (2012)

⁴⁸ Larsson (2012); Stanton et al. (2011)

⁴⁹ Stanton et al. (2011)

⁵⁰ Jones (2013); Cho et al. (2006); Fancher et al. (1998); Jamson et al. (2011)

⁵¹ Muhrer et al. (2012)

⁵² Rosenfeld et al. (2015); Stanton et al. (2011)

⁵³ LeBlanc et al. (2006)

⁵⁴ Stanton et al. (2011)

⁵⁵ Jones (2013); Ma (2005); Matthews et al. (2001)

⁵⁶ Muhrer et al. (2012)

⁵⁷ Stanton et al. (2011)

⁵⁸ CAR analysis. No specific scientific reports have been found.

⁵⁹ Jones (2013); Wickens and Hollands (2000); Young and Stanton (2001)

4.1 TRUST, RELIANCE

Trust and reliance are very important human factors to consider when talking about the adoption and real-life use of AVs, especially because trust in technology takes a long time to build and an even longer time to repair when lost or eroded.

In general, using automation can sometimes lead to incorrect levels of trust:

- Misuse: “users violate critical assumptions and rely on the automation inappropriately”;
- Disuse: “users reject the automation’s capabilities and do not utilize the automation”;
- Abuse: “designers introduce an inappropriate application of automation”.⁶⁰

Several studies have shown that, in the case of highly reliable systems, users tend to be complacent, to over-rely on automation, thus using it beyond its intended scope or failing to remain vigilant for potential malfunctions.⁶¹ Over-reliance on automation is also believed to be responsible for loss of skill and mode confusion. Conversely, a system perceived as unreliable or not proficient will not be used, regardless of any potential benefits.⁶² In addition, research findings indicate that initial perceptions of reliability levels affect subsequent reliability estimates and trust ratings.⁶³

According to other studies, automated driving systems that provide information about the driving goals were more trustworthy and acceptable than systems that did not supply information.⁶⁴ Moreover, informing drivers about situations in which the automation is uncertain improved operators’ trust in the AV technology and their reliance on the system.⁶⁵

System reliance has been found to vary with age. Younger drivers displayed less dependence on automation, and took less time to verify automation suggestions. Older drivers, on the other hand, reported greater trust in automation and experienced higher workloads.⁶⁶ However, other research results seem to indicate that older drivers underutilize smart technology

⁶⁰ Parasuraman and Riley (1997)

⁶¹ Bahner (2008)

⁶² Cummings and Ryan (2014)

⁶³ Blair et al. (2012)

⁶⁴ Verbene et al. (2012)

⁶⁵ Beller et al. (2013)

⁶⁶ McBride et al. (2010)

because they lack perceived need, lack knowledge of the devices, and perceive the cost to be prohibitive.⁶⁷

One of the earlier research projects on the effectiveness of FCW focused on the impact of alarm timing on driver response and trust. This driving simulator test involved six driving situations which combined three driving speeds (40, 60 and 70 mph) and two time headways (1.7 and 2.2 seconds). The main finding was that alarm effectiveness varied in response to driving conditions. In addition, alarm promptness had a greater influence on how participants rated their trust, than improvements in braking performance enabled by the alarm system. Most drivers expected alarms to activate before they initiated braking actions; when this did not happen, driver trust in the system was substantially decreased, because the alarms were perceived as late alarms. Headway times had a great influence on driver performance and perception of alarms. Specifically, when driving with a long time headway setting, drivers' adaptation to late alarms induced a longer response to the brakes, compared to the 'no alarm' condition, possibly resulting in impaired driver behavior.⁶⁸

Another study comparing trust issues associated with a non-adaptive FCW and an adaptive FCW (that adjusted the timing of the warning to the reactions of each driver) indicated the safety benefit of both of these systems. This driving simulator investigation involved 45 experienced simulator drivers. When the FCW system was activated, brake reaction times were reduced and during the braking events drivers maintained a greater distance from the lead vehicle. Results indicated a difference in trust related to FCW between aggressive (high sensation seeking, short followers) and non-aggressive (low sensation seeking, long followers) drivers. In spite of the safety benefits, the aggressive drivers rated each FCW more poorly than non-aggressive drivers did. The latter preferred the plain FCW to the adaptive FCW. Conversely, aggressive drivers, with their greater risk of involvement in rear-end collisions, preferred the adaptive system, as they found it less irritating and stress-inducing.⁶⁹

Concerning ACC, one survey of drivers who had this function on their vehicles showed that as experience with ACC increased, drivers became more aware of the functioning and, especially, the limitation of the system.⁷⁰

⁶⁷ Mann et al. (2007)

⁶⁸ Genya and Richardson (2006)

⁶⁹ Jamson et al. (2008)

⁷⁰ Larsson (2012)

4.2 CARRYOVER EFFECTS, BEHAVIORAL ADAPTATION

When an effect "carries over" from one experimental condition to another, it is called a carryover effect. There is evidence that AV technology has carryover effects and influences driving performance, especially after drivers return to manual control. For example, drivers using CACC tend to become accustomed to the very close time gaps used by the automation. They will also tend to continue at similar gaps even after resuming manual control, thus creating potentially dangerous situations.⁷¹

The notion of carryover effects is linked to behavioral adaptation, which in the case of AVs relates to the behavior changes that occur to drivers using this technology. If in general behavioral adaptation increases a being's chances of survival, when it comes to traffic safety, behavioral adaptations to automation sometimes have negative consequences. For example, several research efforts indicated that drivers tend to misuse the increased safety margins that ADAS features provide, by adapting their driving style (e.g., increasing their driving speed and paying less attention to the driving task than when driving without ADAS).⁷² Other research evidence suggested that factors like age, gender, degree of experience, personality traits, and driving style influence behavior changes.⁷³

Nevertheless, some scientific reports also revealed positive changes in drivers' behavior that are linked to automation. One study showed that drivers using ACC (and even conventional cruise control) had about 3 to 6 mph lower maximum speed compared to manual driving and spent less time at limit-violating speeds. It appears that having to consciously set the speed maintained by the ACC at discrete time-points contributes to better regulation compliance, than continuously adjusting the speed with the accelerator pedal.⁷⁴ However, a research consensus this point does not exist; an earlier study actually found that drivers went faster with ACC.⁷⁵

A study focusing on behavioral adaptation examined to what extent the effect of FCW on response performance is moderated by repeated exposure to a

⁷¹ Jones (2013)

⁷² Kovordányi et al. (2005); Rubin-Brown and Parker (2004)

⁷³ Saad (2004)

⁷⁴ Vollrath et al. (2011)

⁷⁵ Hoedemaeker and Brookhuis (1998)

critical lead vehicle braking event. The trial, performed on a moving-base simulator, also studied whether these effects depended on how critical the events were (i.e. available time headway when the lead vehicle starts to break). The response times and accelerator release times became significantly shorter with repeated exposure for both the FCW and baseline groups (without FCW). The tests showed that the effect of FCW depended strongly on both repeated exposure and initial time headway. Drivers with FCW had faster braking response times than those without it. The effect of event repetition on response times was much larger for FCW drivers.⁷⁶ These results provide an example of positive behavioral changes induced by driving automation.

Another investigation focusing on lane departure warning found that this feature made participant drivers less aggressive on average. Moreover, carryover effects were identified, as the warning triggered an overall 9 percent increase in the rate of turn signal usage. Furthermore, the LDW system made drivers more aware of the fact that they were not using turn signals as often as they should have.⁷⁷

Risk compensation or risk homeostasis is another concern linked to carryover effects. According to this theory, drivers begin to accept more risk, because they perceive the automation to be more competent. This could in turn lead to more distraction and reliance on the automated driving system.⁷⁸

4.3 SITUATIONAL AWARENESS, DISTRACTION

Situational awareness (SA) is defined as the perception of environmental elements in time and space (operational dimension), the comprehension of their meaning (tactical dimension), and the projection of various changes in their status (strategic dimension). Researchers generally believe that, over time, engaging in secondary tasks while driving deteriorates the skills related to the three aspects of SA aforementioned, therefore lowering driving performance. This is an alarming prospect, because critical situations (e.g., automation malfunction, unexpected events) require quick reactions and a high level of SA.⁷⁹

⁷⁶ Aust et al. (2013)

⁷⁷ LeBlanc et al. (2006)

⁷⁸ Cummings and Ryan (2014)

⁷⁹ Endsley (1995)

A relative consensus in the research world is that human attention represents a limited resource and that the brain needs a certain level of stimulus to maintain attention and performance levels high. Research results have shown that drivers tended to engage more in secondary tasks as the level of automation increased, thus becoming potentially more distracted. It was also observed that drivers were more likely to perform secondary tasks when the lateral control was automated, versus longitudinal control.⁸⁰ In a relatively straightforward environment, performing secondary tasks was not found to be detrimental to driving performance. Especially when faced with a demanding task, drivers' attention on the roadway increased.⁸¹

A survey of drivers using the ACC on their vehicles, showed that this technology is associated with lower situational awareness and mode confusion. Some participant drivers reported they had forgotten whether the ACC was activated or not. They were therefore less able to determine whether a situation required their intervention or not. This research also revealed that because of a lack of feedback from the ACC (the system accelerates and decelerates without any indication it will do so), drivers could only react after the system had performed the action or when they realized the system was not taking action as expected.⁸²

Studies on brake response time (BRT) when using ACC clearly demonstrated the highly negative effects of distraction and reduced SA. Drivers using ACC had much higher BRTs than drivers with manual control did, even when the braking event was expected or easily could have been anticipated. In addition, deceleration rates with ACC were twice as large as those with conventional cruise control, and substantially less safe than those during manual driving, therefore demonstrating a reduced SA.⁸³ Finally, a similar study showed that drivers assisted by automation braked only after the collision alert sound and significantly reduced the minimum time to contact. Drivers also performed the worst when they tried to regain manual operation from the ADS system.⁸⁴

These conclusions are not unanimous among the research community and not all technologies have the same effect on SA. A recent study (driving simulator, 30 participants) analyzed driving and gaze behavior, as well as the engagement in a secondary task, when drivers used a forward collision

⁸⁰ Carsten et al. (2012)

⁸¹ Jamson et al. (2013)

⁸² Larsson (2012)

⁸³ Young and Stanton (2007)

⁸⁴ Merat and Jamson (2009)

warning (FCW) and braking system (FCW+). The analysis of the gaze behavior showed that driving with the FCW+ system did not lead to a stronger involvement in secondary tasks. Moreover, the FCW+ shifted the attention of the drivers toward the cockpit when the visual symbols of the Human-Machine-Interface (HMI) appeared. In this test, a substantial number of crashes occurred in the critical situations (e.g., a lead car braking unexpectedly) without FCW+. Conversely, using the FCW+ resulted in significantly fewer crashes, because the automation reacted significantly earlier than the drivers could. Although the drivers were able to detect the deceleration on the lead car at the same moment as the system, they were not able to react fast enough, which made the fast autonomous intervention of the system necessary.⁸⁵

4.4 WORKLOAD

Workload represents the overall level of attention that a task or group of tasks demand from a person. The Yerkes-Dodson Law stated that human performance is optimal when workload levels are in between the extremes.⁸⁶ As the complexity of tasks increases, the workload increases, and the ability to handle supplementary tasks decreases. However, a workload that is excessively low can also be detrimental, resulting in fatigue or distraction.

Experience performing a task tends to lower workload. Consequently, a novice driver's workload level may be very high even with basic vehicle control tasks, which leaves little attention resources for other tasks like traffic prediction or danger identification.⁸⁷

Most research results showed that automation would reduce workload. In addition, it has been shown that this effect was augmented as automation increased. For instance, automated steering induced greater workload decreases than ACC, compared to manual driving.⁸⁸

This can be a great advantage, when drivers use this additional attention capacity to other driving tasks, such as monitoring the environment to identify

⁸⁵ Muhrer et al. (2012)

⁸⁶ Wickens and Hollands (2000)

⁸⁷ Stanton and Marsden (1996)

⁸⁸ De Winter et al. (2014)

potential hazards or to predict changes in traffic. However, this attention transfer is not automatic, as drivers may also focus on non-driving tasks.

There are several hypotheses on how AV technology will affect drivers' workload, with no clear consensus on how the reduced workload of automation affects drivers in critical situations.

- Attention resource degradation hypothesis: as the human operator is no longer actively focused during automation control periods, attention resources may shrink in order to adapt to the reduction in demand.⁸⁹ Therefore, when the driver resumes manual control, the attention demand increases very quickly and performance may be inadequate to ensure a safe transfer of control and overall driving.⁹⁰
- Attention resource conservation hypothesis: as the attention demand is low during automated control, the driver can rest and replenish their cognitive resources. Thus, when needed (e.g., reacting in a critical situation), the driver will be able to deploy their cognitive resources.⁹¹
- Compensation hypothesis: the driver is able to recognize and compensate for a higher workload demand and increase their performance, possibly due to an increase in their general motivation level.⁹² However, this theory does not seem to apply to complex tasks.

Nonetheless, some of the most recent research showed that the need to retake manual control of the vehicle when attention is directed to a non-driving task can lead to dangerous and sudden changes in workload that can have a negative impact on driving safety. For example, it has been shown that performance deteriorated if the driver had to resume control to change lane due to an incident on the road.⁹³

4.5 MANEUVERING SKILLS

As it has been previously stated, prolonged use on AV technology may cause a loss of skill, especially when it comes to higher levels of automation, which

⁸⁹ Young and Stanton (2002)

⁹⁰ Based on conclusions from human factors research in aviation automation, namely Weiner (1989) and Billings (1991)

⁹¹ Based on the limited capacity theories of Kahneman (1973) and Wickens (1980), and on the depletion and replenishment research of Ariga and Lleras (2011)

⁹² Based on research by Sanders and Baron (1975)

⁹³ Merat et al. (2012)

may lead a substantial loss of skill over time. This is a tendency observed with many types of automation.

Maneuvering skills that could be negatively affected by automation include:

- Maintaining longitudinal and lateral control
- Parking
- Respecting traffic signs, reacting to different traffic situations (e.g., speedway, inner city)
- Handling weather conditions (e.g., rain, fog, snow, ice, nighttime)
- Reacting to unexpected situations (e.g., vehicle failure, crash avoidance)
- Interacting with other vehicles or participants in traffic.

Some evidence suggests that, after using AV technology, drivers show poorer lane keeping performances, shorter headways, or delayed reaction times, compared to drivers that have not used this type of features.⁹⁴ In addition, tests have proven that the type of automation support (longitudinal versus lateral) has a different impact on drivers' engagement and performance.⁹⁵ Other research teams did not expect that dual-mode vehicles would cause a loss of skill, because drivers would still partly use their vehicles manually, for automation levels 1 to 3.⁹⁶

Research on crash causation argues that the ability to detect and control traffic hazards improves uniformly as the amount of miles travelled increases. Therefore, the crash rate per unit of exposure will decline as the amount of exposure increases.⁹⁷ Hence, as automation will decrease the number of vehicle miles actively driven, drivers will no longer possess the skills to avoid a dangerous situation that cannot be handled by the automation.

⁹⁴ Merat et al. (2014), Eick and Debus (2005)

⁹⁵ Carsten et al. (2012)

⁹⁶ Toffetti et al. (2009)

⁹⁷ Elvik (2006)

5 HUMAN CAPACITY TO REACT TO FAILURES AND LIMITATIONS OF AUTOMATED VEHICLES

Research teams all over the world have studied drivers' capacity to react to failures and limitations of CAV technology. This is a complex and vast topic, especially given that a great number of technologies are not yet fully developed. Therefore, many questions that have been raised need additional research. For now, studies have focused on the comprehension of warnings, the willingness to pay attention, driver performance, and the impact of automation reliance.

In the case of limitations of technology, the ability to resume manual control was studied for expected and unexpected requests for transfer of control over the vehicle. The tests focused on ACC, as well as other forms of automated longitudinal or lateral control. Driver reaction in the case of an automation failure was mainly tested for ACC, traffic jam assist and object detection. Results give insights on lane keeping ability or steering wheel movements; crash evasion, avoidance of critical events, or braking; and attention toward road center.

In all likelihood, while using automation, drivers respond faster to expected than to unexpected take-over requests. This hypothesis is coherent with situations in which, while manually controlling the vehicle, drivers brake faster when they are reacting to an expected or predictable event.

While automation limitations can result in predictable take-over requests, automation failures, by their very nature, will be unexpected. And it is likely that drivers will have little or no experience in adequately controlling this type of situation. It is therefore widely believed that in the case automation failures, drivers will have longer response times than those for predictable transfers of control.

Moreover, earlier studies indicated that increases in automation could lead to a reduction in SA levels of drivers, therefore contributing to an impaired performance during system limitations or failures.⁹⁸ This should be taken into consideration in the broader conclusion that crashes are more likely to happen when drivers are not paying attention to the road and are not prepared to intervene.

⁹⁸ Endsley and Kaber (1999)

5.1 DRIVERS' REACTIONS TO LIMITATIONS OF AUTOMATED DRIVING SYSTEMS

For vehicles belonging to NHTSA automation levels 1 to 3, drivers are required to resume manual control in traffic situations that are beyond the programming of the CAV technologies. That does not seem to be the case for level 4 vehicles, at least not according to the current definition of this type of vehicle.

Research has proven that operators' ability to resume manual control after a period of automated driving depends on the conditions in which the transfer was requested (i.e. expected, unexpected request for transfer, critical event requiring transfer). For instance, an expected transfer of control is performed when ACC is deactivated as the driver prepares to exit a highway. Conversely, control may be transferred unexpectedly. One particular case of unexpected transfer may be required in the case of a critical event occurring during what would normally be an automated period (e.g. a vehicle stopped on the road, a pedestrian crossing, a crash between preceding vehicles, etc.).

PERFORMANCE AFTER AN EXPECTED TRANSFER OF CONTROL

One study compared the performance of drivers during an expected takeover of control (with prior warning) from automated steering, ACC, and fully automated mode.⁹⁹ Throughout the simulated vehicle test, 47 drivers between the ages of 18 and 24 needed to react to several events: pedestrians crossing the road, a car stopping without warning in front of the driver, a car cutting into the driver's lane. Part of the events occurred during manual driving and part of them during automated driving. In the latter condition, drivers were given a warning and after seven seconds they had to resume manual control.

This study showed that, in terms of lane-keeping ability, after a period of partial or fully automated control, drivers performed significantly worse immediately after resuming control. In addition, within the first four seconds after the control transfer, drivers performed significantly poorer in terms of steering behavior. Concerning crash evasion ability, no significant differences were observed, even five seconds after resuming manual control. This could imply either that the events were not challenging enough or that the twelve

⁹⁹ Johns et al. (2015)

seconds between the transfer warning and the event itself were sufficient to reduce the effects of the preceding automated section.

These findings seem to sustain the compensation hypothesis, in that drivers are compensating for higher workloads during the transfer of control. Therefore, the automated driving does not have an important negative effect on their performance.

PERFORMANCES AFTER EXPECTED VS. UNEXPECTED TRANSFERS OF CONTROL

A different research team compared drivers' capacity to resume control from a highly automated vehicle at a regular interval, on the one hand, and at an irregular interval (based on the period of time when the drivers were looking away from the road), on the other hand.¹⁰⁰ The results of the study are based on the participation of 37 persons in a driving simulator test.

Overall, results indicated that drivers performed better when control was transferred after a fixed duration of six minutes, compared to when the transfer was triggered by a loss of visual attention to the road center. Resumption of manual control, particularly in terms of steering behavior, was worse when the automation was disengaged due to a lack of attention from the driver.

The results of the study indicated that it took 10-15 seconds for a driver to resume manual control, and around 40 seconds to finally reach an adequate and stable control. In concrete terms, visual attention continued to be erratic for up to 40 seconds after the transfer of control, compared to the performance after a programmed transfer. Researchers concluded that this interval of 40 seconds might be considered a "comfortable transition time" as required by the NHTSA level 3 standard.

These findings are consistent with earlier ones, which indicated that if the need to resume manual control is unexpected, almost all drivers crash¹⁰¹, but if they receive prior warning, almost all will avoid the collision.¹⁰²

¹⁰⁰ Merat et al. (2014)

¹⁰¹ Flemisch et al. (2008)

¹⁰² Gold et al. (2013)

PERFORMANCE WHEN EXPERIENCING CRITICAL EVENTS

While using a vehicle with the ADS engaged, drivers have proved to be slower to recognize critical issues and to react to emergency situations (e.g., emergency braking). A great wealth of research shows that, when faced with critical events, drivers perform more poorly (i.e. long response times, near-collisions or collisions) in conditions of higher levels of automation, than in manual driving conditions. However, as it was stated in the previous section, drivers are better at resuming manual control when they are warned of the critical events, than when they must do so unexpectedly.

A test, part of the CityMobil research project, compared drivers' responses to critical events during manual and automated driving (in this case, lateral and longitudinal automated control on a designated eLane).¹⁰³ In a driving simulator, 39 drivers were involved in a car following task and experienced a series of situations that could not be handled by automation. Drivers were alerted of critical situations by an auditory alarm and were required to regain control of the vehicle. For this study, the critical events were: a car emerged from a side road and merged in front of the lead vehicle (linked to longitudinal control); an oncoming vehicle turned right to enter a side road, crossing the path of the lead vehicle (longitudinal); the traffic lights changed to red (longitudinal); the road was partially blocked by a parked car or a reversing truck (lateral).

Overall, findings revealed that drivers responded slower to critical events in automated driving conditions, compared to manual driving conditions. Drivers also anticipated slower these events. In the automated scenario, drivers only reacted to the critical events once they heard the alarm, which seems to indicate either that their SA was lower than in the manual control scenario or that they relied too heavily on the automation.

Specifically, drivers' time to contact and minimum headway with the lead vehicle were much shorter during the longitudinal critical events in the automated driving condition. Results also pinpointed a difference between the three longitudinal events. The drivers anticipated and responded more quickly and appropriately to the changing lights event, compared to the other two events. The 'emerger from left' scenario proved to be the most difficult for drivers, with the shortest response times during both the manual and automated driving conditions.

¹⁰³ Meral and Jamson (2009)

In the automated driving condition and for all critical events, the majority of drivers braked after they heard the alarm. This finding implies that safety was compromised, when compared to manual driving.

Finally, almost one in five drivers did not disengage the HAD system, thereby allowing the vehicle to drive over the speed limit.

Other driving simulator tests concur that drivers' response times depend on the type of critical event, as well as on the type of distraction (i.e., cognitive vs. visual distraction).¹⁰⁴

In a traffic sign scenario, a study found that only 37% of the participants consistently intervened (i.e., braked or disengaged the automation). For those who reacted, they did so on average 275 feet later than during manual driving.¹⁰⁵

Another test (driving simulator, 22 participants) found that drivers using ACC took between five to ten seconds longer to reduce their speed manually in curves or weather conditions (fog), than drivers that did not use ACC. This indicates that drivers take some time before noticing that the system is not able to handle a situation and that they need to override the automation. This may be because drivers had reduced situational awareness or because they needed time for the transfer from automated to manual control.¹⁰⁶

There is also evidence that driver performance varies with the period between the transfer to manual control and a road hazard situation (in this specific study: two, five or eight seconds).¹⁰⁷ Results from a 12 participants driving simulator test demonstrate that few drivers in the two seconds scenario were able to react correctly in the road hazard situation. The majority of participants in the five and eight seconds scenario were able to safely negotiate the hazard. Hence, five seconds seems to be the minimum interval of time necessary for the drivers to properly resume manual control of the vehicle. More research is necessary to test the intervals between two and five seconds, to see what the absolute minimum is.

Another research project studied the reactions of drivers in borderline traffic conflicts, where drivers either resumed manual control or not.¹⁰⁸ Results from

¹⁰⁴ Gold et al. (2014) ; Radlmayr et al. (2014)

¹⁰⁵ Damböck et al. (2013)

¹⁰⁶ Vollrath et al. (2011)

¹⁰⁷ Mok et al. (2015)

¹⁰⁸ Larsson (2013)

this 31 participants driving simulator test revealed a difference between experienced and unexperienced users of ACC. Drivers that had less experience with ACC tended to exhibit a more cautious behavior, i.e. not delegating either manual or monitoring control to ACC. They also retook manual control before ACC started to respond to the critical situation.

5.2 DRIVERS' REACTIONS TO MALFUNCTIONS OR FAILURES OF AUTOMATED DRIVING SYSTEMS

Research has been indicating for the last 20 years that it is highly probable drivers will have a reduced ability to detect and react to automation failure.

FAILURES OF ADAPTIVE CRUISE CONTROL

Early test track results indicated that drivers were late in resuming manual control after an ACC failure (unwanted acceleration).¹⁰⁹ This was consistent with another test, which also found that a third of the drivers that were equipped with ACC and experienced an unwanted acceleration collided with a preceding vehicle.¹¹⁰

Recently, a research team studied drivers' performance in a driving simulator when faced with different types of ACC failures: unwanted acceleration, complete lack of deceleration, partial lack of deceleration, and speed limit violation. The 48 participant drivers were not given warnings or any other indication of the failures. Results revealed that failures in the longitudinal control can lead to critical situations and in some cases to collision.¹¹¹

This test also highlighted drivers' exact reaction to a lack of deceleration or an unwanted acceleration. They showed that, faced with these failures, more drivers preferred steering or changing lanes than braking.¹¹² These results are also coherent with previous findings that showed drivers' tendency to respond to these types of failures by steering or by steering and braking, but not solely by braking.¹¹³ One explanation put forward is linked to the separation of tasks (i.e. ACC has longitudinal control and the driver has lateral control). Results

¹⁰⁹ Rubin-Brown and Parker (2004)

¹¹⁰ Stanton et al. (1997)

¹¹¹ Nilsson et al. (2013)

¹¹² Nilsson et al. (2013)

¹¹³ Stanton et al. (1997). Park et al. (2006) also indicates that steering is a common reaction to ACC failures.

seem to indicate that the drivers preferred steering in a critical situation because braking would mean taking back control from the automation. In other words, drivers may feel that longitudinal control is the responsibility of ACC and, consequently, they intervene only after the situation becomes critical. This seems to imply that either the drivers were reluctant to retake control away from the automation or that they tolerated some degree of ACC malfunction before intervening.¹¹⁴

This last explanation is also coherent with the reactions to the speed limit violation. Results showed that one in six participants did not react at all, and that the average response time for those that slowed down was 15 seconds.

The ‘partial lack of deceleration’ failure proved to be the most dangerous. Specifically, partial lack of deceleration caused more crashes than complete lack of deceleration (43% compared to 14% of the participants colliding with a preceding vehicle). Researchers believe that, when seeing that the ACC was beginning to decelerate, drivers were misled into thinking that the system was in fact working properly. The participants understood only too late that the system was malfunctioning and that the braking applied by the ACC was insufficient.

However, this study also shows that both minimum time to collision (TTC) and minimum headway time (THW) for complete lack of deceleration were shorter than those for partial pack of deceleration, a tendency contrary to the number of collisions. This may be because even if the deceleration was partial, those drivers that did identify the failure were given more time to respond. This indicates that in order to increase safety, drivers should be made aware of a failure while the system decelerates as much as possible.¹¹⁵

FAILURES OF ADAPTIVE CRUISE CONTROL VS. TRAFFIC JAM ASSIST

Earlier studies focusing on failures of automation having both longitudinal and lateral control found that half of the participants in a driving simulator test failed to resume control of the vehicle and to apply the brakes in order to maintain a safe distance to the preceding vehicle.¹¹⁶

There is evidence that drivers react in a distinct manner for different levels of automation. A test compared ACC with traffic jam assist (TJA), which has

¹¹⁴ Nilsson et al. (2013)

¹¹⁵ Nilsson et al. (2013)

¹¹⁶ De Waard et al. (1999)

longitudinal and lateral control. Drivers' reactions were measured for three degrees of failure (moderate, severe, complete failure to decelerate).¹¹⁷

No significant differences in performance were found for the three types of failure. However, more safety critical and fewer successful transfers of control were associated with TJA, the higher level of automation, than with ACC, even though the failure only affected longitudinal control in both cases.

FAILURES OF OBSTACLE DETECTION TECHNOLOGY

Recent research brought evidence of the effects that error type, error distribution, age and experience can have on driver performance in the context of an automation malfunction. The test was performed on a virtual agricultural vehicle equipped with obstacle detection technology. 60 younger adults and 60 older adults participated in the test. The study focused on the mechanisms of reliance on automation.¹¹⁸

Results suggest that the link between automation reliability and driver reliance is determined by the types of system failures. Concretely, a predominance of automation false alarms led drivers to under-rely on automation during alarm intervals and to over-rely on it during non-alarm intervals. On the contrary, when faced with a greater number of automation misses, drivers over-relied on the system when an alarm was given, and under-relied on it during alarm-absent intervals.

Younger, as well as older, drivers adjusted their behavior according to the performance of the automation. However, older participants were slower to do so. They also relied less on automated alarms than younger participants did. These results are not completely consistent with earlier findings, which concluded that when automation failed, older drivers exhibited a greater dependence on automation and rated their trust in automation higher than younger drivers did.¹¹⁹

FAILURES OF AUTONOMOUS LANE CHANGE

Another research project was directed at drivers' reaction to failures of an autonomous lane change system. The simulator was based on the lane change test and introduced three types of automation failure: lane change when signs

¹¹⁷ Nilsson (2014)

¹¹⁸ Sanchez et al. (2011)

¹¹⁹ McBride et al. (2010)

indicated straight driving (commission error), no lane change when signs indicated a change (omission error), lane change when required, but incorrect lane (commission error). The 28 participant drivers were instructed to react to the automation failure by steering the correct way.¹²⁰

Results indicated that drivers reacted faster to fix commission errors, than omission errors, since they involve vehicle movement. Findings also revealed a learning curve, i.e. the deviation from the lane was the greatest for the first error. The more the drivers were faced with automation errors, the smaller the deviation until they reacted. This finding seems to be consistent with the ‘first failure effect’, i.e. that the first automation failure results in a more pronounced drop of trust and reliance on the automation than subsequent failures.¹²¹

There were two scenarios of automated steering in this study: in the first one, the steering wheel remained in a neutral position, and in the second one, the wheel moved as the virtual car moved. The latter scenario generated much shorter response times to automation errors, than the former. This implies that the drivers took less time to direct their attention to the road if they had steering wheel movement feedback, which is the scenario closest to real-life conditions.

The findings also gave insights on the impact of secondary tasks on drivers’ ability to react to automation failure. Results clearly indicated that active tasks were responsible for the deterioration of the ability to supervise automation. Tasks requiring visual attention away from the road or tasks that involved active engagement in particular were more detrimental, whereas auditory tasks were less so.

FAILURES OF COLLISION MITIGATION SYSTEMS

A recent study investigated driver behavior when the automatic steering of a collision mitigation system was activated. One of the driving simulator tests, performed with the help of 40 participants, involved a false alarm, i.e. the system was falsely triggered in a non-collision situation and the vehicle swerved without a reason. The goal was to test the controllability of the crash mitigation system in the case of a false alarm.

¹²⁰ Spiessl and Hussmann (2011)

¹²¹ Wickens and Xu (2002)

The results showed that the drivers handled the false alarms quite well. The controllability of the system seemed to be tolerable. The average value for the maximum lateral deviation (2.65 feet or 0.81 meters) before the drivers took back control of the vehicle was rather small compared to the width of the lane (10.66 feet or 3.25 meters). The average time needed to bring the vehicle back into its lane after the system intervention was 745.9 ms, which represents a rather fast reaction.¹²²

5.3 IMPLICATIONS ABOUT DRIVERS' PERFORMANCE

The evidence presented in this chapter points out that operating vehicles with an increasing level of automation, is linked to an 'out of the loop' problem, a loss of skill, a loss of awareness of the state and processes of the system¹²³, an increasing difficulty troubleshooting and recovering control of the vehicle when needed.

Over time, the skill degradation can further reduce drivers' ability to respond to emergent driving demands. While acting as a supervisor, it is highly likely that the driver's workload will be low. This may cause the driver to become bored or perform secondary tasks, thus feeling out of the loop.¹²⁴

The changes in drivers' responsibilities, namely the transition from operator to systems supervisor, can also result in sudden changes in workload, which can cause 'automation surprises', that occur when human operators lose track of what the automation is doing.¹²⁵ This is essentially a human factors problem, caused primarily not by flaws with either automation or operators as such, but instead by failures in the design of the human-machine interface.

Faced with a system error, the driver will probably also experience a sudden and potentially unmanageable increase in workload, as the driver will be forced to regain control of the vehicle in a quick and adequate manner. This will prove to be a challenge over time, as with high automation, the task of managing a system failure will become more difficult.¹²⁶

¹²² Fricke et al. (2015)

¹²³ One of the earlier research efforts are presented in Endsley and Kiris (1995) and Stanton and Marsden (1996)

¹²⁴ Toffetti et.al. (2009)

¹²⁵ Woods et.al. (1994)

¹²⁶ Bainbridge (1983)

Therefore, to identify automation failure, the operator must either know exactly how the technology works or be provided with the necessary feedback on whether the system is working properly. Unexperienced drivers, who never faced an automation failure or relied only on CAV technology, may not be able to identify a malfunction or to adequately resume manual control when needed. Studies that measure drivers' ability to spot system errors indicated signs of troubleshooting complacency for the participants that had not faced automation failures during training sessions.¹²⁷

Therefore, precisely when the automation system needs assistance from the driver, the latter may not be able to provide it or may actually make the situation worse by reacting in an inadequate manner.

Some researchers conclude that we cannot assume that the drivers operating these new vehicles will always be engaged, informed, ready to act and make the right decisions.¹²⁸ This seems to be a contradiction, or at least a challenge for level 2 and 3 vehicles. On the one hand, these vehicles are advertised as giving drivers the possibility to focus more on secondary tasks, but, on the other hand, may require keeping drivers in the loop, in case these might need to resume manual control.

¹²⁷ Bahner et al. (2008)

¹²⁸ Cummings and Ryan (2014)

6 IMPLICATIONS OF CONNECTED VEHICLE APPLICATIONS FOR DRIVER PERFORMANCE AND SKILLS

Connected-vehicle based warning systems have their own spectrum of driver acceptance and performance issues. In contrast to driving automation, research on the impact of the use of connected vehicle applications on driver performance and skills is more limited.

USDOT researchers have used Safety Pilot data to investigate potential for drivers to become distracted or over-reliant on connected vehicle technology. The V2V applications that were tested were: forward crash warning, emergency electronic brake light, intersection movement assist, blind spot detection, left turn assist, and do not pass warning. A survey of Safety Pilot drivers yielded a range of opinions on such issues. A minority of participant drivers declared becoming more distracted when using the CV applications (6 percent). More participants deemed the applications untrustworthy (25 percent) or found the warnings confusing (48 percent).¹²⁹

Driving simulation studies of intersection movement assist (IMA) and left turn assist have uncovered similar results. The participants who received the IMA alert and crashed nevertheless, indicated that they believed drivers would pay less attention to the road than those who did not receive the alert. Also, some participants found the IMA alerts confusing. This is why the people who received an IMA alert and did not crash rated the IMA alert as more clearly indicating why it was warning the participant than those participants who experienced a crash.¹³⁰

The full extent of connected vehicle implications on driver skills is unclear because test deployments have thus far been limited. Many results from sensor-based warning systems are likely extensible to V2V-based systems. However, the driver skills implications of V2V-based systems are more complicated than those of V2I applications because the driver will only receive warnings when another vehicle in potential conflict is equipped with DSRC technology.¹³¹

¹²⁹ Stevens (2013)

¹³⁰ Balk (2013)

¹³¹ GAO Report to Congress (2013)

7 LESSONS LEARNED FROM AUTOMATION IN AVIATION

Experience gained from aviation automation can be very useful when considering the ability of drivers to respond to failures or limitations of automated vehicles. This concerns topics such as the sharing of authority, the consequences of over-reliance on technology, and skill degradation.

The role of a pilot monitoring an aircraft autopilot system is somewhat similar to that of a driver in a highly automated car. However, the comparison between aircraft pilots and drivers, either commercial or regular, has its limits. The training and standards applied to the performance of aircraft pilots are much higher than those for automobile drivers. Due to the specific architecture of the commercial aviation sector, the resources dedicated to training individual pilots in order to adapt to changes in their role due to automation are greater than those that will be available to react to the automation in the automotive sector. Nevertheless, the changes in pilots' skills caused by automation, can give valuable insights on the expected evolutions of automobile driving skills.

Another limit to this comparison is linked to the driving and flying environment. The aviation context is relatively simple when compared to a typical driving context. Control of the aircraft in the three axes can be translated in simple mathematical equations. In addition, the pilots have several internal and external aids for navigation and monitoring of the surroundings. Road environment on the other hand is far more complex and unpredictable, as there are far more potential interactions with other drivers, cyclists, pedestrians, etc.

Automation has had a significant impact on pilot manual performance in aviation. The main problems relate to degraded manual-flying skills, poor decision-making, and possible erosion of confidence, when automation abruptly malfunctions or disconnects during an emergency.

In order to counteract skill degradation, in aviation, pilots are regularly required to disengage the automated systems in order to refresh their training.¹³² The FAA as recently started recommending that pilots fly more in manual mode than in autopilot mode.

¹³² Barley (1990)

Recent research points out that it is not the loss of manual skills that is important, but that of cognitive ones. This team studied 16 experienced pilots on routine and non-routine flight scenarios in a Boeing 747-100 simulator. Levels of automation available to the pilots were varied as the researchers analyzed pilots' performance. The participants also reported what they were thinking about as they flew.

The researchers found that pilots' ability to scan instruments and manually control the plane was mostly intact, even when pilots reported that they infrequently practiced these skills. However, when it came to cognitive tasks needed for manual flight (e.g., tracking the aircraft's position without the use of GPS, deciding which navigational steps come next, recognizing system failures), pilots experienced more frequent and significant problems in performing them manually. Furthermore, pilots who relied more heavily on automation and who were distracted during flight were more likely to lose their cognitive skills.¹³³

In one of its most recent reports, the Federal Aviation Administration identified ways in which the flight path management task may be compromised, as a result of knowledge and skill vulnerabilities due to prolonged use of automation:

- “Knowledge Issues: Pilot knowledge of the basic airplane systems is not as detailed as in the past.”
- “Practice and Exposure: Long term use of FMS¹³⁴-derived flight path trajectory without the need to critically assess or intervene may atrophy the skills needed to anticipate, monitor and react. “
- “Understanding of underlying systems: Procedures and training practices may emphasize the use of autoflight modes, procedural execution and selections rather than facilitate an understanding of the architecture, logic and algorithms of how those modes and selections relate to the flight path management task, from the pilot's perspective.”
- “Deviation and off-path management: Flight crews manage or react to deviations and off-path situations in extremely variable ways, and training is often limited in this area. While this inconsistency is found within operations that are subject to the same procedural guidance and training

¹³³ Casner et al. (2014)

¹³⁴ Functional Movement Systems

program, the variation in practices observed is common across the industry.”¹³⁵

Automation in aviation also has many valuable insights about the problems that can human operators of automated vehicles might experience and the extent to which they might represent a safety risk. The most important psychological factors to take into consideration are boredom and inattention because of low workload, cognitive strain under conditions of very high workload, failure of automated systems to meet pilots’ expectations, and over-reliance on the technology.¹³⁶

The Nagoya accident of 1994 (China Airlines Airbus A300) was a landmark case that began to raise awareness on the difficulties that flight crews have with automation.¹³⁷ Recent aviation incidents also illustrate the serious consequences of some of these problems.

- Distraction can cause pilots to miss important input from the automation or the environment (Eastern Flight 401)
- Pilots might see the cues but not have all the appropriate information in order to make a correct decision (Air France Flight 447), or
- They might use their spare capacity to engage in distracting activities leading to a loss of SA (Northwestern Flight 188).

¹³⁵ Federal Aviation Administration (2013)

¹³⁶ Young, et al. (2007)

¹³⁷ “While the co-pilot was manually flying the ILS approach to runway 34 at Nagoya, and descending through 1,000 feet, he inadvertently activated the go-around switches (also referred to as the GO lever) on the throttles, activating the auto-throttle go-around mode. This resulted in a thrust increase and a climb above the glide path. The copilot attempted to return to the glide path using forward yoke. Subsequent engagement of the autopilot while in go-around mode caused the trimmable horizontal stabilizer (THS) to drive the stabilizer towards its nose up limit as compensation for the manual control inputs via the yoke. The first officer continued his effort to maintain approach glide path with forward yoke, commanding the elevator in the airplane nose-down direction (opposite the THS driven by the autopilot system). Passing approximately 510 feet, the captain took control of the aircraft, which was now in an extreme mis-trim condition, and applied longitudinal control to the maximum elevator-down limit in opposition to the maximum nose-up stabilizer position. Unable to overcome the greater aerodynamic force of the stabilizer, the crew initiated a go around. On the application of go around thrust, the aircraft rapidly pitched up and airspeed steadily decreased. Correspondingly, airplane angle-of-attack (AOA) increased sharply. The captain was unable to arrest the climb, which continued to approximately 1,700 feet, and AOA increased until the aircraft stalled. Unable to recover from the stall, the aircraft crashed into the landing zone approximately 340 feet east-northeast of the centerline of the approach end of runway.” – FAA website, retrieved May 12, 2016
http://lessonslearned.faa.gov/l_main.cfm?TabID=3&LLID=64

The most significant safety concern associated with automation in commercial aviation is mode confusion, in which they take decisions believing that the system is in a different state than in reality.¹³⁸ This is related to earlier findings of lack of mode awareness (i.e., the current and future status and behavior of the automation). As a result, pilots may experience automation surprises when the automation takes an unexpected action or does not behave as anticipated.¹³⁹ Many aviation incidents and crashes have been linked to mode confusion and automation surprises.

Therefore, while automation has been essential in reducing the accident rate in aviation, many accidents that were labeled as human error by the Federal Aviation Administration (FAA) and the National Transportation Safety Board (NTSB) could be better characterized as failures of human-automation interaction. More specifically, several recent plane accidents were primarily caused by inappropriate responses of pilots to automation failures in correctable situations.

The challenges in terms of human-automation interaction are well summed up by the difference in the philosophies of Boeing and Airbus. Boeing's take on automation is that the pilots have ultimate authority and that automation should only assist, not replace them (soft automation). Conversely, Airbus believes that automation should enhance aircraft and system performance, therefore preventing the pilot from inadvertently exceeding safety limits. Technology has the ultimate authority and can override the human operator's inputs (hard automation). Both philosophies have their advantages and disadvantages. Hence, Boeing allows the pilot to commit errors that can lead to incidents, whereas Airbus may prevent an experienced pilot from executing a maneuver needed for safety. This illustrates that the designers of automated technology can grant the final decision authority either to the automation or to the human operator. This point can also be made about road vehicles. For example, if automated emergency braking systems will probably prevent many crashes overall, in some instances, a crash can be better avoided or mitigated by swerving rather than braking. However, this technology may not allow for this. Therefore, vehicles with these systems may be slightly more likely to crash in these instances.

¹³⁸ Cummings and Ryan (2014)

¹³⁹ Sarter and Woods (1997)



8 CONCLUSIONS AND RECOMMENDATIONS

For the last 30 years, research has been discussing how drivers' skills and performances change under the influence of new technologies that make vehicles increasingly automated and connected. Although there are many nuances, most researchers agree that, for drivers, automation will probably be linked to a loss of skill, a loss of awareness of the state and processes of the system, and an increasing difficulty for troubleshooting. In addition, most researchers agree that when people resume manual control after a period of automation control their performances are poorer when compared to those of drivers who only used the manual mode.

Because CAV technologies are still in development and most likely decades from being adopted on a mass scale, it is difficult to make reliable projections on whether the negative effects of technological dependents in driver skills will offset the benefits of driving automation (i.e. fewer accidents, less congestion, enhanced human productivity). Experience from the introduction of other driving automation applications can give an indication of the complex impact these technologies on traffic accidents.¹⁴⁰ Further research is needed in order to perform a cost-benefit analysis of the use of ADS. Understanding the balance between benefits of ADS and risks associated with loss of driver skills, further information is needed notably on the likelihood of ADS failures and of misuse or abuse of ADS by drivers, as well as analysis of interactions in mixed traffic situations (autonomous vehicles with different levels of automation engaged, non-automated vehicles, pedestrians, cyclists, etc.).

The expected drivers' loss of skill and loss of awareness of vehicle status raises a number of questions and challenges that the automotive industry, the regulatory authorities, as well as individual drivers will need to address in order to ensure a safe and successful adoption of CAVs.

For the short and medium term, we need to understand the implications of having simultaneously on the streets vehicles belonging to different levels of automation and greater numbers of less experienced drivers. Does this imply, for instance, the need for some form of exterior identification for vehicles operating in automated mode, as some have suggested? When in traffic, will a

¹⁴⁰ For example, studies have shown that ABS had no overall effect on fatal crash involvements, because it was associated, on the one hand, with a decrease in multi-vehicle crashes and fatal pedestrian strikes, and, on the other hand, an increase in single-vehicle road departure crashes. (NHTSA, 1999, and NHTSA, 2009)

driver using manual control be able to communicate its intentions to a fully autonomous vehicle, especially if the passenger of the latter vehicle is not paying attention? Also, how much time will drivers need to get accustomed to the way automated vehicles behave in traffic?

The potential heterogeneity of CAVs raises another challenge: the harmonization of technologies. Should OEMs seek harmonization (with respect to the interactions between driver and automation, the type of tasks that are automated, or safety features, for example)? Can this be solely market-driven or do NHTSA and state regulators need to design certain standards? If the standardization of these new technologies will not occur in the short to medium term, should manufacturers propose training modules designed for their newest vehicles? Would partnerships with dealers be necessary to deliver this training, and will dealers be qualified to provide it?

By and large, the redefinition of driving and navigating responsibilities between the human and the vehicle software is a crucial evolution brought on by automation. This change will likely have an impact on human-machine interfaces, driver training and licensing, responsibility assessment in case of a code violation or crash, insurance policies, etc.

8.1 CHALLENGES LINKED TO DRIVERS AND VEHICLE OPERATION

There is currently no clear consensus on the nature of the interaction between drivers and automated vehicle systems. One school of thought argues that “the driver cannot be relied upon to act as a monitor if moment-to-moment vehicle control is taken away”.¹⁴¹ The second school of thought asserts that the human operator plays a vital role in an automated system¹⁴² and that the driver should not have a passive role.¹⁴³ The challenge is to take this debate from academia and industry to the greater public, so that regular drivers understand what their role might be in future vehicles.

Researchers indicate that the transitions between automated and manual control will likely prove to be difficult for drivers. Improving human-machine interfaces (HMI), so that drivers resume manual control of the vehicle faster

¹⁴¹ Jacoby and Schuster (1997)

¹⁴² Merat and Lee (2012), Nilsson (2005)

¹⁴³ De Waard et al. (1999)

and safer is one of the greatest challenges on the road towards connected and automated vehicles. In this sense, drivers might need to change the way they learn and maintain their driving skills.

FIGHTING DRIVER DISTRACTION

Research findings point out the risks of requiring potentially distracted drivers to resume manual control of their vehicles. This implies that, especially for NHTSA level 1 to 3 vehicles, many more issues linked to shared or alternate authority between human operators and automated systems need to be solved before this technology is safely released to the greater public. For example, should drivers be required to remain attentive at all times, even when they do not have manual control of the vehicle, as part of the research community suggests?¹⁴⁴ Some automakers and suppliers are already working on technologies that will monitor a driver's condition and attention level.¹⁴⁵ Conversely, other players like Google have so far taken the stance that intervention or constant monitoring from a person will not be required at all in fully autonomous vehicles.

The automotive industry and the relevant public authorities will need to work together to minimize the risks posed by the question of shared or alternate effective control. Drivers experience a learning curve in regards to understanding the amount of attention they can redirect to secondary tasks without becoming too distracted to monitor automated driving systems.

UNDERSTANDING CAPACITIES AND LIMITATIONS OF TECHNOLOGY

The second challenge for drivers will be to understand the new capacities and limitations of CAV technology and to act accordingly. Avoiding the abuse or misuse of these new technologies is a challenge for drivers, but also for the industry and public authorities. All must collaborate to reduce the risk of abuse and misuse through general information, training and design of HMI. National campaigns such as "My car does what"¹⁴⁶ are just one of the ways that drivers can gain information on CAV technologies.

¹⁴⁴ For instance, Merat and Jamson (2009)

¹⁴⁵ GM and Delphi are reportedly developing a driver monitoring feature for the "SuperCruise" that will be available on Cadillac 2016 or 2017 models.

¹⁴⁶ "My car does what" is funded by the Toyota Safety Research and Education Program Settlement and developed independently by the University of Iowa and the National Safety Council.

LIMITING LOSS OF SKILL

Finally, loss of skill due to prolonged use of automation will prove to be an important issue, if a great number of CAVs will require shared or alternate effective control. As it is done in the aviation sector, it may become necessary establish procedures for minimum manual driving periods or recurrent training on simulators (for vehicles that will still offer the option of manual operation), to ensure that drivers do not lose their skills and can cope with automation failure.

ATTRIBUTING RESPONSIBILITY FOR FAILURES OR CRASHES

Attributing responsibility in case of failures or crashes of autonomous vehicles is another legal and technical challenge that will affect the use of autonomous vehicles. Some legal experts believe that product liability will have an increasing importance in failures of autonomous vehicle technologies. In this case, all companies on the supply chain are potentially liable. In October 2015, Volvo, Mercedes, and Google announced they would take full responsibility in crashes involving an autonomous vehicle, whenever one of their cars is in autonomous mode. So far, these are only declarations and by the time autonomous vehicles are actually for sale, the legal responsibility needs to be fully clarified by the appropriate legislative or regulatory agencies.

8.2 CHALLENGES LINKED TO VEHICLE DESIGN

ENSURING SAFETY AND SECURITY

One of the most important challenges for the automotive industry linked to the topic of this report is ensuring that CAVs have very high levels of safety and security. This is crucial for example for reducing the probability that human intervention is unexpectedly needed in complex traffic situations, or minimizing the risk of cyber-attacks on vehicles. The industry is currently working on multiples ways to improve safety and security. Industry players seek inspiration from other fields that are highly protected against cyberattacks and require near 100% availability rates, such as aviation, defense, or nuclear energy. One of the ways to contribute to ensuring security and safety is the redundancy of systems, which minimizes the risk of system failure. This is used for example in the aviation, but from an economic standpoint is this viable in the automotive industry?

SEEING AUTOMATION AS A COOPERATIVE EFFORT

For all vehicles except the fully autonomous ones (NHTSA level 4), the majority of research findings implies the importance of keeping the driver in the loop at all times.¹⁴⁷ In this case, human operators and automated systems should be seen to a certain extent as co-pilots. Engineers, researchers and the public should perceive “driving automation as a cooperative effort between humans and technology—one where the human plays a vital, active role in systems that optimize the interaction between the driver and the technology.”¹⁴⁸ For the design of connected and automated vehicles, this stance implies a challenge to develop systems that interact with drivers.

The starting principle is that the human operator and the automation need communicate and coordinate to ensure the safe operation of all non-fully autonomous vehicles, as the experience from aviation automation has shown. In addition, intent must be mutually communicated between the human operator and the automation.

First, the system needs to monitor the driver’s state for a number of reasons: to avoid driver distraction, to ensure that the driver is capable of resuming control of the vehicle when needed, etc. Within the industry, a variety of technologies are being considered for this task (cameras, alcohol detectors, vital signs monitors, etc.).

Second, the driver needs to be able to monitor what the automation is doing, how and why. The driver must be involved and continually informed about the status of the automated systems. In general, tests show that this type of information, through a diagnostic function, helps drivers identify and react faster in the event of an automation failure. Research also suggests that it is more efficient to provide drivers with continuous information about the state of the system, than to warn them about imminent crash risks in the case of automation failures.¹⁴⁹ Some researchers suggest that the more powerful automated systems become, the more feedback they need to give in order to make their behavior observable to the human operators.¹⁵⁰ From a human perspective, if the capabilities and the actions of the automation are more transparent, the problems linked with trust, workload and mental models will decrease. However, it is important to identify the optimum amount of

¹⁴⁷ For instance, Merat and Jamson (2009)

¹⁴⁸ Nees (2015)

¹⁴⁹ Seppelt and Lee (2007)

¹⁵⁰ Christoffersen and Woods (2000)

information, so as not to overload the driver with information or provide too little content. Research has provided some insights on best practices. For example, driver performance improves when information on right-of-way regulations, obstructed intersection views, and safe gaps to change lanes or merge with traffic are provided, resulting in safer driving without increased workload.¹⁵¹ Haptic feedback (e.g. for steering) has proven to be the most effective way in keeping the driver informed.¹⁵² In addition, multimodal displays that combine visual, auditory and tactile information may be useful for keeping the human operator informed about the actions taken by automation.

MAINTAINING OPTIMUM LEVELS OF SITUATIONAL AWARENESS

As previously shown, automation can reduce the situational awareness (SA) of drivers. When developing HMIs, it is therefore essential to apply design principles to support SA and prevent the loss of SA. For example:

- Organize information around the driver's goals,
- Present comprehension information directly, to support driver understanding,
- Provide assistance for projections (what will happen next),
- Support overall SA (board awareness of total situation),
- Support trade-offs between goal-driven and data driven processing,
- Make critical cues for "schema activation" salient (to support responding).¹⁵³

HMI systems should be designed in order to prevent the loss of SA because of: attentional tunneling, data overload, misplaced salience, complexity creep, errant mental models, out-of-the-loop syndrome, requisite memory trap (overload of working memory), stressors (workload, anxiety, fatigue).¹⁵⁴

Another idea to keep drivers engaged is adaptive automation, where the system strategically gives some control of the vehicle back to the driver at regular intervals. The challenge is designing vehicles equipped with very high computing capacities, and even deep learning skills, as well as HMIs that are highly efficient in keeping the driver informed and involved.

¹⁵¹ Davidse et al. (2009)

¹⁵² Spiessl (2011)

¹⁵³ Endsley et al. (2003)

¹⁵⁴ Endsley et al. (2003)

A slightly different approach to automation is to monitor a driver's performance and to intervene only when it seems they are about to make an error or a potentially dangerous maneuver. This also requires equipping vehicles with deep learning capacities, to understand and adapt to a driver's specific style of driving.

DETECTING MALFUNCTIONS OF THE AUTOMATED DRIVING SYSTEM

An important component of the design of CAVs will be the capability of vehicles to detect malfunctions of the automated system, and to inform drivers in a way that enables them to regain proper control of the vehicle.¹⁵⁵ In addition, vehicle manufacturers will likely need to research and develop backup systems that can take over the automated tasks in case of a failure.

8.3 CHALLENGES LINKED TO THE REGULATORY FRAMEWORK

When CAVs are deployed, especially self-driving or highly automated vehicles, current training and licensing procedures may become inadequate. Changes may need to be introduced in training and licensing procedures.

As previously stated, changes in the role of the driver will likely have an impact on driving requirements. However, as long as automated vehicles offer manual control as an option, most of the requirements for human drivers will remain valid: that the person be licensed, not intoxicated or impaired, etc.

Regulatory groups, such as NHTSA, and industry groups, such as the Society of Automotive Engineers (SAE) On-Road Automated Vehicle Safety (ORAVS) committee are currently wrestling with how to tackle these issues. The approaches taken by industry groups and federal regulators could impact the responsibilities of state agencies such as MDOT and the Secretary of State.

MAKING CHANGES IN DRIVER TRAINING

As CAV technology is developed and deployed, it is likely that the current testing criteria for drivers will need to evolve, in terms of skills and knowledge, as well as medical conditions. This change in training

¹⁵⁵ For the moment, NHTSA (NHTSA, 2013) requires this feature for vehicle testing.

requirements may need to be gradual, following the evolution of CAV technology.

It is likely that the new CAV technologies will prove to be a challenge for current training systems. It is possible that dealers and manufacturers will gain a more important role in training. Insights from current methods to learn how to use CAV features show for example that drivers that had training modules in dealerships considered these modules very useful and wanted to use this method more in the future.¹⁵⁶

New training systems, whether they involve third-party driving schools, manufacturers, or dealers, should ensure that drivers have acquired the necessary skills for operating a particular type of automated vehicle, that they are fully aware of the capabilities and limitations of the vehicle, as well as the distribution of roles between the human operator and the automation, that they are able to make successful transfers of control between manual and autonomous driving.

NHTSA recommendations on the specific training for test drivers of self-driving vehicles are a useful input to start the discussion for new training schemes for the greater public. NHTSA recommended that training courses include “an understanding of the basic operation and limits of self-driving vehicles, and knowledge of how to resume control of such a vehicle in the event that it cannot continue to operate automatically”.¹⁵⁷ In addition, NHTSA recommended that these training modules be “submitted to the state agency that issues driving licenses for approval prior to the taking of that course by any person seeking a driver’s license endorsement certification”.¹⁵⁸ A comparison of the training done by a few companies that are currently testing autonomous vehicle technology reveals substantial differences: Google has a 5-week program, but most of the other companies have a one day course or less.¹⁵⁹

The differences in the driver-vehicle interaction according to the automation levels raise the question whether there should be specific training modules for each of these levels. The modules should clearly explain the task distribution between the driver and the automation, the interaction between the two, and the limitations of technology. However, there are other issues. What should

¹⁵⁶ JD Power (2015)

¹⁵⁷ NHTSA (2013)

¹⁵⁸ NHTSA (2013)

¹⁵⁹ Harris (2015)

we teach drivers with respect to the adequate involvement in secondary tasks, distractions and workload management? How will training cover emergency or critical situations, system malfunctions, and troubleshooting from a theoretical and practical perspective? Part of this training could be done more efficiently in a simulator than in real traffic. A driving simulator would be particularly useful for error training, where participants can commit their own errors as they actively explore the driving task. Experiments have shown that error training is more efficient as it leads to significantly fewer errors and safer driving practices in performance tests.¹⁶⁰

In the future, training could play a role in alleviating the long-term impact of automation on the degradation of driving skills. In the aviation industry, pilot skills are monitored and periodic custom trainings are provided to ensure skill retention or improvement. This is a good inspiration for driving automation. Transportation companies will probably be among the early adopters. The challenge will be to design a scalable model for regular drivers, because this represents a fundamental change in the content and dissemination of driver training. We might wonder whether it is necessary to go from the current system, in which training is essentially provided before obtaining a license, to a system where training is viewed as an on-going or at least periodical obligation for the driver. It is still to be determined who will be the players involved in such a training scheme, but in the automotive industry possible methods are already being developed. One option is to rely on simulator training. Another idea is to make on-going training part of the HMI. Combining driver monitoring and deep learning computers would make personalized, dynamic training modules possible. However, driver skills monitoring raises important questions about privacy and disclosure of information to authorities.

Automated driving (for vehicles equipped with levels 1 to 3 ADS and level 4 vehicles that also have a manual operation mode) may contribute to making driver training more complex, customized, and costly. This is because training may reduce the risk of loss of skill and awareness, and thus the risk of performing poorly in situations where drivers may need or want to manual operation of the vehicle.

¹⁶⁰ Ivancic and Hesketh (2000)

State licensing authorities should work in close cooperation between themselves, with NHTSA, and with automotive manufacturers to define training requirements and procedures.

CHANGING DRIVER LICENSING PROCEDURES

As with training, it is likely that the evolution of driver licensing will be best organized as a gradual process, following the deployment of automation. State legislators and agencies, the federal level and the automotive industry should cooperate in order to determine to what extent the evolution towards automation and, to a lesser extent, connectivity will require changes in licensing.

Evolution in drivers' role and skills are not the only input for this discussion. Aspects linked to responsibility and legal liability, which were not part of the scope of this report, also need to be considered. To help in this discussion, the distinction between an effective driver and a virtual driver could be useful in determining what type of licenses should be delivered and to whom.¹⁶¹

Because drivers' responsibilities and therefore skills will evolve, it might become necessary to change or introduce new license categories. The endorsements on U.S. driver's licenses and the license categories used in the European Union (see Figure 6) for particular types of vehicles are a useful comparison.

¹⁶¹ Smith (2012)

FIGURE 6. EUROPEAN DRIVING LICENSE CATEGORIES

A 	> 50 cm ³ > 45 km/h (alt. max. 25 kW - 0.16 kW / kg)	C 	 < 750 kg
A1 	max. 125 cm ³ max. 11 kW 16 < max. 80 km/h < 18	CE 	 > 750 kg
B 	max. 3.5 t max. 8+1   < 750 kg	D1 	 < 750 kg max. 16+1 
BE 	 > 750 kg	D1E 	 > 750 kg max. 16+1  max. 12t
C1 	> 3.5t, < 7.5t max. 8+1   < 750 kg	D 	 < 750 kg
C1E 	 > 750 kg max. 12t	DE 	 > 750 kg

If different types of vehicles such as motorcycles and heavy trucks require specific training and licensing today, should we introduce new license endorsements, once CAVs are ready to hit the market? What should we base these endorsement categories upon? Are the NHTSA levels of automation sufficient for instance? Moreover, vehicles that offer both manually and automated control as an option pose a challenge. A CAV used in full manual mode is driven the same as a traditional vehicle, but requires different tasks and skills in automated mode.

NHTSA recommendations for licensing drivers to operate self-driving test vehicles are one source of inspiration. “The issuance of a driver’s license endorsement (or separate driver’s license) to a person should be conditioned upon certain prerequisites, such as that person’s passage of a test concerning the safe operation of a self-driving vehicle and presentation of a certification by a manufacturer of self-driving vehicles (or the manufacturer’s designated representative) that the person has successfully completed a training course provided by that manufacturer (or representative), or a certification by that manufacturer (or representative) that the person has operated a self-driving vehicle for a certain minimum number of hours.”¹⁶²

A report prepared by a group for researchers from Carnegie Mellon University for the Pennsylvania Department of Transportation¹⁶³ recommends that specific driving and skills tests be required for all automation levels (with the exception of NHTSA level 4). The testing criteria could be periodically

¹⁶² NHTSA (2013)

¹⁶³ Hendrickson et al. (2014)

updated to assure the drivers' basic understanding of the CAV technology functioning, regulatory and liability issues, and the types of interactions between driver and automation. That might prove to be a challenge if vehicles have features that operate differently.

The administration of sanctions for code violations is also partly linked to the driver's license. If the human operator's role and legal responsibilities change, however, then how sanctions are attached to a license also might need to change. Many wonder whether automated driving may result in fewer code violations, if autonomous vehicles are programmed to respect the rules. Will we need to reconsider the way sanctions for code violations or crashes are made? Who will be held responsible and how will that translate when talking about driver's license and driving privileges? Does automated driving challenge the very definition of responsibility currently used in the Michigan Vehicle Code? This important discussion involving academia, public authorities, insurance companies, and automakers has intensified in the last five years.¹⁶⁴

To have a sustainable and safe licensing system, coordination efforts likely will be needed at the national level and perhaps even internationally.

¹⁶⁴ These questions are discussed more in detail in an earlier CAR report, "Automated Vehicle Technology Development and Deployment. Opportunities and Policy Implications for the State of Michigan", prepared for MDOT in 2013.

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APPENDIX A: LIST OF ABBREVIATIONS

ABS	Anti-Lock Braking Systems
ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance Systems
ADS	Automated Driving Systems
AEB	Automated Emergency Braking
AS	Automated Steering
CCC	Conventional Cruise Control
CAR	Center for Automotive Research
CAS	Collision Avoidance System
CAV	Connected and Automated Vehicle
CWS	Collision warning system
ESC	Electronic Stability Control
FCW	Forward Collision Warning
IMA	Intersection Movement Assist
ITS	Intelligent Transportation Systems
MDOT	Michigan Department of Transportation
TJA	Traffic-Jam Assist
SAE	Society of Automotive Engineers (SAE) On-Road Automated Vehicle Safety
ORAVS	(ORAVS)