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# How challenges of human reliability will hinder the deployment of semi-autonomous vehicles

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ABSTRACT

This perspective article explores the impacts that the transition period to fully autonomous driving will have on human reliability and how these challenges will become major hurdles in the safe deployment of the technology. In particular, the analysis focuses on the potential contribution of Automated Driving Systems (ADS) towards safety, the specific role of human errors in this field and how driver distraction and its associated risks are exacerbated by the introduction of ADS. Additionally, the link between Autonomous Vehicle (AV) usage and risky driving behaviour is discussed, as well as the issue of interaction between AVs and other road users.

## 1. Introduction

In order to improve the safety of car occupants and other road users, the automotive industry moved its focus from improvements in passive safety to the development of technologies enabling active safety. Some earlier technological development concentrated on enhancing the ability of specific systems to perform the driver's intention in adverse conditions; prominent examples include Anti-lock Braking System and Electronic Stability Control, commonly referred to as ABS and ESC, designed to limit skid and loss of steering control, which both became mandatory for new cars sold in the European Union. On the other hand, some systems are designed to reduce driving errors by alerting drivers of potentially hazardous situations through the use of sensors scanning specific risks and an adequate warning protocol; this applies to Forward Collision Warning (FCW) and Lane Departing Warning (LDW) systems for example. In all these instances, the human driver remains the nerve centre of the vehicle, fully and solely responsible for detecting and assessing the risk (possibly assisted by a warning system) and taking appropriate action (whose performance may be enhanced by a control system). With technological progress, these complex systems can start interacting such as in Adaptive Cruise Control (ACC), leading to the implementation of avoidance or mitigation strategies better able to address drivers' deficiencies: the human operator can now be temporarily bypassed in case of inaction during emergency situations. Collectively referred to as Advanced Driver-Assistance Systems (ADAS), these have been shown to contribute to improvements in road safety (Cicchino, 2018, 2017; Fildes et al., 2015). Nowadays, the most refined ADAS constitute Automated Driving Systems (ADS), whose increasing level of complexity and capability paves the way for the development of Autonomous Vehicles (AVs) (Chan, 2017). Given the wide range of current and predicted aptitudes, the degree of driving automation is being defined by the industry standard SAE J3016 (SAE International, 2014, SAE International, 2018) comprising 6 levels ranging from no automation to full automation (cf. Fig. 1). Due to the need for supervision or intervention of the human driver, levels 1 through 3 are regarded as semi-autonomous, with fully autonomous vehicles at levels 4 or 5.

## 2. The potential impact of ADS on road safety

The wide-ranging benefits of ADS typically include the potential for “fewer traffic collisions, due to elimination or minimization of human errors” (Chan, 2017, p. 211), however the individual and societal benefits of AVs also cover “comfort, convenience, mobility, energy, environment, and economy” (Chan, 2017, p. 215): whereas safety formed the basis of early ADAS, the safety performance of more advanced systems might be seen as a constraint to a feature designed for other purposes. In fact, Sivak and Schoettle consider that “it is not a foregone conclusion that a self-driving vehicle would ever perform more safely than an experienced, middle-aged driver” (2015, p. 7), while Kockelman et al. (2016) reflect on the sensing capability of automated cars which, similarly to a human driver, degrades in extreme conditions. Crucially, Chan highlights that “most impacts, including […] increased traffic safety […] will only be significant when autonomous vehicles become affordable and represent a major portion of total vehicle travel” (2017, p. 212), noting “the deployment issues or implementation challenges that may be difficult to resolve for the moment” (2017, p. 211). This is echoed by the findings of Sivak and

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



**Fig. 1.** Standard levels of driving automation, defined by SAE International, 2014.

Schoettle that "when conventional and self-driving vehicles would share the road, safety might actually worsen, at least for the conventional vehicles" (2015, p. 7), predicting that the transition period would last several decades considering an average vehicle age over 10 years and the positive skew of the vehicle age distribution.

While full AVs certainly incorporate very complex technologies, the technical capabilities of these systems are extensively studied in order to perfect their performance and robustness (Kwon et al., 2005; Park and Oh, 2019; Song et al., 2018; Wang et al., 2015; Wang and Li, 2019). But Kockelman et al. identify the challenges posed in level 2 and 3 by "the shared authority between human drivers and automation components" when driving conditions require the ability to switch seamlessly between the two (2016, p. 18). Intuitively, this appears to be a major concern for level 3 automation when the human operator is no more in charge of supervising the system and yet is expected to take control of the vehicle if required. This manoeuvre can be safe only if planned or if the "autonomous driving systems fail gradually and gracefully" while any sudden transitioning of the authority will be particularly dangerous (Sparrow and Howard, 2017, p. 207). For semi-autonomous vehicles, reliability studies should therefore include the failure of human-machine interactions, for example as an intermediate event in a fault tree, and make a clear distinction between different types of handovers, for which McCall et al., propose the taxonomy of "scheduled", "non-scheduled system initiated", "non-scheduled driver initiated", "non-scheduled driver initiated emergency" and "non-scheduled system initiated emergency" (2019, pp. 514–515). These five forms of handover situations apply differently to different levels of autonomous driving and, crucially, some are part of the system design (e.g. "scheduled handover") while others are directly attributed to a system fault (e.g. "non-scheduled system initiated emergency handover"). To enable the quantification of these failures, some initial insights of the handover events can be gained from the analysis of AV trials: Favarò et al. present "trends of disengagement reporting, associated frequencies, average mileage driven before failure, and an analysis of triggers and contributory factors" for vehicles tested on California public roads (2018, p. 136). The authors of this study categorise handovers as "human factors", "system failure", "external conditions" and "other" (Favarò et al., 2018, pp. 140–141); while system failures, linked to hardware or software, represent over 50%, it can be argued that handovers due to "external condition" (11%) relate to the inability of the system to safely operate and thus are a failure of the system as well. However, it is important to keep in mind that these are drawn from a test phase and cannot be generalised since it required "the presence of a control driver who has to undergo a specific training" (Favarò et al., 2018, p. 136) and the technology is conceivably going to improve as an outcome of the trial, so further studies will be required in this area to obtain a better understanding of these critical handover events.

## 3. The evolving landscape of human errors

For many years, researchers have sought to better apprehend driver behaviour and the impact of errors on road safety. The Driver Behaviour Questionnaire (DBQ), developed by Reason et al. and published in 1990 (Reason et al., 1990), "is a well-documented instrument for obtaining self-report information on aberrant driving behaviors" (Zhao et al., 2012, p. 676). Designed to measure "lapses, errors and violations", the DBQ "has become one of the most widely used instruments for measuring both driving style […] and the relationship between driving behaviour and crash involvement" (Martinussen et al., 2013, p. 228). The DBQ has been extensively revisited to look at a range of countries and driver characteristics, and through a meta-analysis of 174 studies published in 2010 de Winter and Dodou (2010) identified that errors and violations from the DBQ correlate to involvement in prospective as well as retrospective accidents. The underlying cause of this relationship has aroused interest, with studies aimed at linking selfreported DBQ results with observed driving behaviour on instrumented vehicle or simulator (Helman and Reed, 2015; Zhao et al., 2012).

While this body of knowledge regarding operator errors is a useful input for reliability studies on conventional vehicles, its validity in the case of semi-autonomous vehicles is questionable. Indeed, numerous studies investigate the capacity of human operators to maintain high levels of concentration as controls were taken away. Merat et al. (2014) find that it takes around 35 s for drivers to regain proper control of the vehicle when automation stops, and that the attention towards the road was higher when handover events were more predictable. Interested in the driver's physiological response to system failure, Arakawa et al., al. indicate that “cognition level during autonomous driving is lower than that during manual driving” which led to mind distraction when required to resume control after a system failure, noting the level of stress experienced by drivers dependent on ADS during handover (2019, p. 587). Highlighting the key role of distraction in handover performance, Merat et al., al. show that “in the absence of the secondary task, drivers' response to critical incidents was similar in manual and highly automated driving conditions” but that “the worst performance was observed when drivers were required to regain control of driving in the automated mode while distracted by the secondary task” (2012, p. 762). The level of distraction between automation levels 0, 1 and 2 has received particular attention, with Carsten et al. (2012) finding that engagement in non-driving tasks increased as automation gradually increased from level 0 to 2, while results from Strand et al. similarly indicate “that driving performance degrades when the level of automation increases” (2014, p. 218). In a meta-analysis of this subject, de Winter et al. conclude that operator's workload increased for semi-autonomous driving (i.e. they “are likely to pick up tasks that are unrelated to driving”) and that while situation awareness may improve compared to manual driving, this was only true if drivers using ADS did not engage in non-driving tasks (2014, p. 196). Significantly, this review confirms that attention levels between level 1 and level 2 automation are markedly different, which Strand et al. succinctly posit as “manual lateral control positively affects monitoring of longitudinal automation” (2014, sec. Highlights).

To better grasp the implications of ADS exacerbating distraction and the associated risks, it is possible to turn to existing work correlating the distraction levels of drivers with the capability to identify dangerous situations (Castro et al., 2019). In the light of the compelling role of driver attention level when using ADS, reliability studies could benefit from the inclusion of this factor in future driving behaviour research, as exemplified by this work attempting to modernise the DBQ to incorporate questions focused on inattention and distraction (Cordazzo et al., 2016). Technology might help to alleviate this specific issue, with proposals to introduce various forms of driver monitoring, but while Atwood et al. highlight the potential benefit of a “driver inattention warning system” in semi-autonomous vehicles (2019, p. 132), there are also evidences that adaptive ADAS based on distraction levels failed to demonstrate a tangible advantage (Reinmueller and Steinhauser, 2019). Another area that would certainly benefit from further research is the role of experience when confronted with ADS. For conventional driving, Castro et al. (2019) point to the fact that experience contributes to higher understanding of dangerous situations, while Larsson et al. (2014) show that the effect of experience materialises differently for semi-autonomous vehicles: despite the increase in response times when using ADS, “this effect was significantly lower for those previously experienced” with the system, illustrating “an element of learning involved not only in knowing about system limitations, but also in responding to potential hazards” (Larsson et al., 2014, p. 229). But the long term impact could be drastic, as Sparrow and Howard postulate that requesting an operator to retake control of the vehicle will become a major concern as “the improved reliability of driverless vehicles is likely to be accompanied by a loss of skill amongst human drivers” (2017, p. 208). Therefore, the current understanding of human errors applied to reliability studies such as fault tree analysis on conventional vehicles might not be replicated to semi-autonomous vehicles, for which the role and the failures of the operator are entirely redefined.

## 4. The psychology of AV usage

Another aspect of human behaviour research gaining traction is associated to perception and social acceptability of AVs (Daziano et al., 2017; Gkartzonikas and Gkritza, 2019; Haboucha et al., 2017; Liljamo et al., 2018; Zhang et al., 2019), which in some instances can illuminate specific risks potentially connected to AV usage. Although Hulse et al. find that “males and younger adults displayed greater acceptance” of this technology, which might have positive road safety implications due to the propensity of these groups to adopt risky driving behaviours, it also warns that these findings were insufficient to draw conclusions on risk-taking (2018, p. 1). In a study of the intention to use AVs, Payre et al. share the following insights (with “fully automated car” referring to level 3 in their analysis):

> Thus, high sensation seekers are expected to intend to use a fully automated car more than low sensation seekers, in order to experience novelty and adventure. However, delegating driving may lower thrill experience while driving. It has been shown that when using an ACC device, high sensation seekers drive on average faster, with shorter headways between vehicles and make stronger braking […]. Thus, high sensation seekers might adapt their behaviour while being driven by an electronic system in their own car by being less careful. (Payre et al., 2014, p. 254)

In the same study, Payre et al. further establish that a large majority of participants are interested in using AVs while impaired from alcohol, drug use, medication or tiredness. They suggest that level 3 automation “might inhibit the feeling of driving, decreasing the need of being in control and being responsible for the vehicle”, leading to potential deliberate misuse of the AVs (Payre et al., 2014, p. 260). The prospect of semi-autonomous vehicles appearing as an attractive technology for risk-takers, either when sensation-seeking or when impaired, is therefore further evidence that reliability studies cannot assume AV operators to behave similarly to the drivers of conventional vehicles. However, as the relation with risk-taking remains so far somewhat speculative, additional work would be required in this field to determine some quantitative results that could be used in fault trees or event trees.

Asides from studies rightly focusing on the effects semi-autonomous vehicles would have on the human operator, another area of interest relates to the interaction between road users and the way AVs would impact existing expectations. Proponents of an evolutionary transition to full automation, whereby levels 2 and 3 are stepping stones towards level 4 and beyond, acknowledge that human drivers are likely to remain part of the driving process due to their ability to perform tasks, such as exchanging “visual glances or body gestures with other drivers to communicate intentions”, that are yet to be mastered by machines (Chan, 2017, p. 210). As drivers “have certain expectations about the likely actions of other vehicles” and perform driving operations “according to the feedback received from other drivers” which would be absent when encountering a self-driving vehicle, the transition period during which full AVs and conventional vehicles coexist will be problematic (Sivak and Schoettle, 2015, p. 5); this study however noted that the importance of expectations and feedback as well as their effects on safety remain to be determined. Interestingly, an examination of test driving in autonomous mode by Google cars from 2009 to 2015 reported no single-vehicle crash while 8 out of 10 accidents were due to a human driver rear-ending the AVs (Teoh and Kidd, 2017). Overall, only 1 of the 10 occurrences led to shared responsibility by the AV, suggesting “that highly-automated vehicles can perform more safely than human drivers in certain conditions, but will continue to be involved in crashes with conventionally-driven vehicles” (Teoh and Kidd, 2017, p.

57). Consequently, analyses of AV trials may shed some light on the issue of safety-related interactions, provided that these studies investigate the root cause of accidents to identify whether the human drivers may have misinterpreted the intentions of the AVs. To avert such misunderstandings in the future, work is being conducted to establish implicit cooperation rules adopted by drivers in circumstances not regulated by law so that these behaviours can be replicated in AVs (Imbsweiler et al., 2018; Kauffmann et al., 2018). Given the specific risks posed to Vulnerable Road Users (VRUs) such as pedestrians and cyclists, their receptivity to different communication features relaying the intentions of the AVs has been the subject of numerous studies which have highlighted the need for self-driving vehicles to provide universally comprehensible information (Ackermann et al., 2019; Deb et al., 2018; Merat et al., 2018; Rodríguez Palmeiro et al., 2018; Straub and Schaefer, 2019). Whether it relates to other drivers or VRUs, the long transition period where AVs and conventional vehicles share the road will likely see a reinterpretation of the perception of intended behaviour, hence reliability studies based on current expectations of road users and associated probabilities will need to be reviewed to match the evolving behaviours of a population getting accustomed to AVs.

## 5. Conclusion

As stated by Fagnant and Kockelman, AVs “represent a potentially disruptive yet beneficial change to our transportation system” with potential impacts on “vehicle safety, congestion, and travel behaviour” (2015, p. 167). This massive shift will need to be accompanied by significant changes in regulations, to first facilitate the testing of self-driving cars on public roads but more importantly support their deployment by clarifying new liability regimes affecting the insurance industry (Schellekens, 2015; Vellinga, 2017; Xu and Fan, 2019). This in turn requires an advanced understanding of the reliability and risks associated with this technological progress. Besides reliability studies focusing on the hardware and software required to bring self-driving vehicles to market, there is a clear need to also cover the impact their usage would have on human operators and other parties in order to enable high-performing semi-autonomous and fully autonomous vehicles.

Current high-quality reliability studies would be relying on a well-established understanding of driver behaviours and road user interactions gained over decades, based on a population familiar with conventional vehicles in real-life conditions and well versed in implicit cooperation rules required to share road infrastructures. With the introduction of sophisticated ADAS, ADS and ultimately full AV technology, it becomes paramount to revise this knowledge to reflect the technical complexity of the systems on hand, but also the intricacy of human behaviours affected by these technologies. The case of full autonomous driving is rather straightforward as fault trees would see the disappearance of events related to manual driving, replaced by new events purely related to failures of the technical operating system. Nevertheless, potential changes in third-party interactions would need to be considered as misreading external factors is a cause of hazardous situations. For partial automation however, fault trees should see a massive increase in complexity, combining failures related to manual driving, technical failures of the ADS as well as new failures associated to human-machine interactions such as emergency handovers. Additionally, for these vehicles it is inappropriate to assume that human errors from manual driving remain unchanged as event frequencies would be altered by the new operator's distraction levels.

There is therefore much further research required in this area, covering topics in a wide variety of disciplines. Indeed, in order to go beyond studies purely focused on technical performance of new systems and which intrinsically consider that there is no larger systemic change in the transport system and the way the vehicle interacts with its environment, an interdisciplinary approach is needed to better integrate social science studies in the engineering analysis of ADS technology. Notably, research to identify failure modes of the technological solutions should have a particular emphasis on failure modes of the interactions, and should lead to the inclusion of these results in the established analysis methods used by the safety and reliability engineering disciplines. Emulating the work done to adjust the DBQ to different socio-economic factors and cultural environments, a similar research effort to explore differences in interaction behaviour across countries as well as cultural and societal settings would prove useful. This endeavour could thus help bring to light potential obstacles regarding the diffusion of AVs in some communities and form a first step toward identifying inclusive deployment strategies, or where necessary targeted actions addressing these specific challenges.

To leverage the ever-increasing number of AV trials, great benefits would come from research to better understand disengagement mechanisms for semi-autonomous driving and how these events would evolve when moving away from a testing environment, albeit on real roads, to real-life usage by untrained and unpaid individuals. Similarly, in-depth investigations of the root causes of accidents during trials would help clarifying the potential contribution of misinterpretation of AV's intentions by other drivers, and thus guide the development of mitigating features for upcoming vehicles. Additionally, while a large body of work already exists regarding driver distraction for low levels of automation, with research covering levels 0 to 2, there is still a dearth of practical studies focusing on operator errors in level 3 automation which appears to be the most precarious since it is both the highest level of semi-autonomous driving and was shown to attract considerable interest from risk-takers (sensation-seekers or impaired users).

Sparrow and Howard noted that “maximising social and environmental benefits of AVs requires strong regulation” (2017, sec. Highlights); specifically, these safety implications are a key point highlighted by advocates of a revolutionary path which would see a leap to level 4 autonomy as semi-autonomous vehicles are banned (Chan, 2017; Sparrow and Howard, 2017). But going further, Sparrow and Howard also predict that eventually, “driving will be made illegal” (2017, p. 209) since “the ethical challenge posed by driverless vehicles” implies that “as long as driverless vehicles aren't safer than human drivers, it will be unethical to sell them” but “once they are safer than human drivers when it comes to risks to 3rd parties, then it should be illegal to drive them” (2017, p. 206).

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## Supplementary materials

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