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Automated driving and its effect on the safety ecosystem: How do compatibility issues affect the transition period?

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Abstract

Different components of automated vehicles are being made available commercially as we speak. Much research has been conducted into these components and many of these have been studied with respect to their effects on safety, but the transition period from non-automated driving to fully automated vehicles raises safety related issues dealing with mixed traffic situations. More in-depth knowledge should be gained in (the safety of) the behaviour of drivers of unequipped vehicles, enabling automated vehicles to predict and adequately respond to potentially unsafe behaviour, a concept we call backwards compatibility. Also, automated vehicle system design tends to be from an optimal system performance perspective which leads to driving patterns such as driving in the centre of a lane. Other (human) road users however likely exhibit driving behaviour in line with different rationales which allow for suboptimal driving patterns. As of yet, it remains unclear whether these patterns contain indications about the intentions of a driver and if or how other road users anticipate these. This could have two consequences with regard to mixed traffic situations. First of all, other road users might miss important cues from the behaviour of the automated vehicle (what we call forward incompatibility). Secondly, the occupant of an automated vehicle might expect human-like behaviour from the automated vehicle in safety-critical situations, lowering acceptance if this does not meet expectations. The current paper considers these issues and states that we need more insight in how road users use other road users' behaviour to anticipate safety critical events, especially in the transition period towards fully automated vehicles.

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Keywords: Automated driving; Driving safety; Driver behaviour; Mixed traffic situations

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1. Background

The concept of automation in the area of transportation is an idea that has been around longer than often thought. The *Futurama* exhibit at the 1939 New York World Fair envisioned an automated highway system within 20 years, with advanced high-speed vehicles using dedicated expressways to comfortably travel across the country. The idea of an automated highway system remained rather futuristic up until 1991, with the signing of the US Intermodal Surface Transportation Efficiency Act (ISTEA) which included a budget to develop the technology required for driverless vehicles on automated highways and mandated the development of an automated highway system test track. This test track was completed by the National Automated Highway System Consortium (NAHSC) in 1997 and a successful public demonstration was held the same year in San Diego. After the NAHSC demonstration however, funding was pulled and attention shifted towards developing nearer-term in-vehicle technologies. In a review of the NAHSC project conducted by the Transportation Research Board it was concluded that, although the focus was now on near-term innovations, technological innovations like highway automation would be crucial to meet long-term safety and capacity needs [1].

Catalysed by the increase in computers' computational power and technological improvements of sensors, the development of in-vehicle technologies is progressing at an increasing rate since the turn of the century. Several advanced driver assistance systems (ADAS) supporting the driver in the driving task are now readily available in commercially available vehicles. Interesting to see is that many of these ADAS use some sort of automation by eliminating operational aspects of the driving task, be it in the longitudinal domain like with Adaptive Cruise Control (ACC) or in the lateral domain like with Lane Keeping Systems (LKS). Where ADAS are usually restricted to isolated parts of the driving task in either one of these domains, recent innovations take automation to the next level and integrate different systems in order to partially or fully automate the driving task. For instance in the VisLab Intercontinental Autonomous Challenge [2] four fully automated vehicles drove 13,000 kilometres from Italy to Shanghai in 2010, and two years later Google announced that their fully automated vehicles reached the 500,000 km mark [3]. It so appears that automation is indeed an inevitable step in the area of transportation and that the current trend, in contrast with the rather top-down automated highway ideas from the previous century, is that automation in the area of transportation is now a more gradual and bottom-up process.

2. Benefits of vehicle automation

At the time of the ISTEA, three important benefits of an automated highway system were posited: improved travel times by reduced congestion and higher speeds, improved fuel economy, and improved safety. This is more or less in line with two generic arguments favouring vehicle automation. First of all, vehicle automation is considered to be a major step towards a more efficient road system, both in terms of producing a more stable traffic flow [4] that reduces the risks of congestion, as well as improved fuel efficiency due to increases in aerodynamic performance [5].

Secondly, automation is also considered a safety improvement. Whilst it is true that the human driver is the most important cause in accident occurrence [6], the accidents themselves remain rather exceptional situations (cf. [7]). It could therefore be argued that vehicle automation in order to improve safety is only required in unsafe situations. Also, several human factors issues could make us question the validity of the assumption that automation results in improved safety at all. Humans can react in unexpected ways to new technologies (e.g., behavioural adaptation; [8]) and can show signs of complacency [9] and over-reliance on the system (cf. [10]) irrespective of system failure. All of these could potentially lower the level of safety, and several ADAS have been studied with regard to implications for safety because of these phenomena (for an overview with regard to behavioural adaptation specifically, see [11] and [12]). It should be noted however that many of these issues might become obsolete when vehicle automation progresses to such a state that there is no need for a driver at all. So achieving the potential safety benefits of vehicle automation and the removal of the driver from the driving task seem to go hand-in-hand.

3. The road to full vehicle automation

That automation is a gradual process is reflected in the levels of automation defined by the Society of Automotive Engineers [13], with higher levels corresponding with increased automation both of the operational driving task (steering, accelerating) as well as the tactical driving task (lane changing, responding to events). Similar taxonomies have also been made by the Germany Federal Highway Research Institute [14] and the US National Highway Traffic Safety Administration [15]. Although these taxonomies are meant to be descriptive rather than normative, classifying progressive levels of automation in relation to how much we have limited driver influence implicitly states that removing the driver from the driving task is ultimately the correct way of driving. All that apparently remains is to meet the technological requirements in order to reach these higher levels of automation. However, the road to fully automated driving is a long one as illustrated by the mere existence of different taxonomies and even by the differences between them, and we often tend to exclude the fact that fully automated driving does not imply the complete absence of the human element from the equation. We acknowledge that the transition to full vehicle automation is an actual and emerging topic and therefore relatively absent in literature, and will attempt to discuss it by separating it in two domains: issues in compatibility between vehicles, and between vehicle and humans.

3.1. The issue of inter-vehicle compatibility

First of all, partly due to the apparent complexity of the technology but particularly due to the fact that not all vehicles will be instantaneously replaced by fully automated ones, there will be a significant transition period where a mixed system will exist of partially and fully automated vehicles as well as unequipped vehicles. And even then, it is not a given that unequipped vehicles will ever completely disappear from our roads. Although fully automated vehicles (and to an extent partially automated ones) could use vehicle-to-vehicle communication (V2V) to streamline headways, speed, and possible notify each other in case of lane changes, they cannot do so in conjunction with unequipped vehicles. For realising the efficiency related benefits of vehicle automation this might not be pressing, but it is crucial to maintain the assumption that vehicle automation will benefit safety: not all sources of information used by human drivers to detect and avoid safety critical situations might currently be available for automated vehicles. In order to guarantee that the safety ecosystem will not be negatively altered, automated vehicles will at least need to be what we call have *backwards compatibility* (see Fig. 1). That is, automated vehicles need to be able to anticipate the behaviour of unequipped vehicles based on externally measurable behavioural indicators like acceleration and lateral position. This way, the introduction of automated vehicles occurs gracefully in the current traffic system, particularly in safety critical situations. However as of now, our understanding of these behavioural indicators lacks both quantification and qualification of what is safe behaviour and what is not [16].

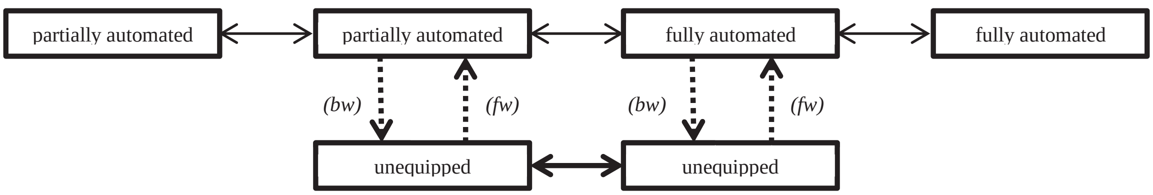

Fig. 1. The different inter-vehicle interactions in a mixed traffic system. The bold lines are dependent on our understanding of human driving behaviour. The dashed lines indicate interactions that require either backwards (bw) or forward (fw) compatibility to prevent safety disruptions.

3.2. The issue of human-vehicle compatibility

A second issue is that of the compatibility between vehicles and humans, which can be subdivided in two categories. First is what we will call the requirement of *forward compatibility* (see Fig. 1). That is, in a mixed traffic system drivers of unequipped vehicles will interact with automated vehicles and might expect human-like driving behaviour from those vehicles as if it were unequipped vehicles. Theoretically, ideal forward compatibility is achieved when the driving behaviour of automated vehicles is completely indistinguishable from that of human drivers. A potential problem here is that the automated vehicle's system design will likely favour driving patterns which are in line with the earlier mentioned benefits of automated driving: optimizing efficiency and/or optimizing safety. Both of these are unlikely to be expected by the drivers of other (unequipped) vehicles, as most human drivers themselves do not pursue constant optimization and generally drive just well enough to accomplish the task at hand, a concept known as satisficing driving [17]. Indeed, achieving forward compatibility could require that the design perspective of automated vehicles needs to change to include more or less 'suboptimal' driving patterns, at least in the transition period when human drivers are inexperienced with other more 'optimal' driving patterns. No research has been conducted so far that investigates the potential importance of goal-related factors such as satisficing driving with regard to the forward compatibility of automated vehicles with human drivers. We stipulate that there is also an apparent lack of research in how and how well drivers can anticipate other driver's behaviour, and how and how well they can anticipate safety related behaviour specifically. So as of yet it is unclear whether the issue of forward compatibility is an issue at all, but if so, it will more likely affect the existing safety ecosystem negatively than positively because of incompatible expectations.

Secondly, vehicles serve a mobility purpose so even fully automated vehicles will usually be occupied by people. At least for the next decades, those people will be experienced in manual driving and still have the expectations that comes from having that experience. The driving patterns exhibited by fully automated vehicles might not always be compatible with the expectations of the occupant of the vehicle, with potential implications for the occupant's *acceptance* of the system (for instance, see [18] and [19]). Although the occupant of a fully automated vehicle is not involved in the driving task itself, incompatibility between the system's workings and the occupant's expectations could at worst lead to a sense of frustration, reducing comfort and hypothetically creating a mistrust of the system. As of yet, there is a lack of research in this area even though gaining more knowledge might be beneficial in the design process of fully automated vehicles. Particularly for partially automated vehicles and even for existing ADAS, where specific aspects of the (operational) driving task are automated but the driver is still required to actively monitor or perform more tactical tasks, it is important that the driver remains 'in the loop' and can anticipate adequately on system failure or system boundaries [20]. With regard to partially automated vehicles and ADAS, acceptance related issues are therefore already discussed in literature [21,22]. More recently, this has even been done with regard to driver experience with automation [23].

4. Future directions for automation compatibility

We raised three issues that could potentially affect the existing safety ecosystem with the introduction of partially or fully automated vehicles. The ability of automated vehicles to anticipate the behaviour of other (unequipped) vehicles, which we call *backwards compatibility*, is argued to be critical to maintain the existing safety ecosystem because we do not know how unsafe driving behaviour is externally measurable. Behavioural indicators that are externally measurable, like speed, longitudinal and lateral acceleration, and lane position might contain clues that could be used to predict upcoming changes in driving behaviour and even an upcoming safety-critical situation. More research here, especially with a focus on real-time analysis, prediction, and framing it in a safety context, is a prerequisite to achieve backwards compatibility.

The interaction between automated vehicles and unequipped vehicles is bi-directional, so additionally we argued that drivers of unequipped vehicles likely expect human-like driving behaviour from automated vehicles. The driving patterns of human-like driving behaviour might contain clues that primes anticipation in human drivers, and it could therefore be beneficial to embed more of this human-like behaviour in the driving patterns of automated vehicles. We call this *forward compatibility*, and to avoid an unexpected disturbance of the current safety ecosystem it could be an essential part of automated vehicle design. A first step here would be to establish if forward compatibility is an issue at all. This could be done by investigating whether human drivers are capable of distinguishing between the driving goal of other (human) road users, for instance between driving just well enough to reach their destination with a sustainable level of safety (satisficing driving) and driving to avoid a safety-critical situation like a collision (which is supposedly more in line with optimal driving patterns). Finally, we argued that occupants of fully automated vehicles could expect human-like behaviour from the automated vehicle. Especially in safety-critical situations, the *acceptance* of the behaviour of the automated vehicle is dependent on the compatibility of that behaviour with the expectations of the occupant. Incompatible behaviour could potentially lead to discomfort with or even mistrust of the automated vehicle. This is inherently a part of making the automated vehicle forward compatible, because it involves the alignment of the automated vehicles' behaviour with what would be expected by humans. We therefore suggest that acceptance and forward compatibility will be studied in close relation with each other.

These issues raised in this paper need to initiate further discussion and raise awareness of their existence, as it is less a question of *if* vehicle automation will be a reality but more a question of *when* and – with regard to the issues raised in this paper and especially during the transition period – of *how*.

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