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Human behaviour with automated driving systems: a quantitative framework for meaningful human control

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ABSTRACT

Automated driving systems (ADS) with partial automation are currently available for the consumer. They are potentially beneficial to traffic flow, fuel consumption, and safety, but human behaviour whilst driving with ADS is poorly understood. Human behaviour is currently expected to lead to dangerous circumstances as ADS could place human drivers 'out-of-the-loop' or cause other types of adverse behavioural adaptation. This article introduces the concept of 'meaningful human control' to better address the challenges raised by ADS, and presents a new framework of human control over ADS by means of literature-based categorisation. Using standards set by European authorities for driver skills and road rules, this framework offers a unique, quantified perspective into the effects of ADS on human behaviour. One main result is a rapid and inconsistent decrease in required skill- and rule-based behaviour mismatching with the increasing amount of required knowledge-based behaviour. Furthermore, the development of higher levels of automation currently requires different human behaviour than feasible, as a mismatch between supply and demand in terms of behaviour arises. Implications, discrepancies and emerging mismatches this framework elicits are discussed, and recommendations towards future design strategies and research opportunities are made to provide a meaningful transition of human control over ADS.

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Automated driving systems; meaningful human control; quantitative framework; human behaviour; skill-; rule-; and knowledge-based behaviour

Relevance to human factors/Relevance to ergonomics theory

Human Factors in automated driving systems (ADS) are currently poorly understood. The relevance of this paper is that it adds to the understanding in a way that it introduces the innovative concept of "meaningful human control", and applies it to the domain of Human Factors in ADS, as well as that it presents a new framework of human control over ADS. With it, this paper elicits several mismatches between what is currently demanded from a driver of an ADS, and what such a driver is actually capable of doing. Furthermore, the discussion of these implications raises directions to future design strategies and research opportunities in the fields of Human Factors.

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1. Introduction

It is becoming increasingly important to address human factors issues with automated driving systems (ADS), as consumer vehicles become equipped with increasing amounts of advanced driver assistance systems that take over parts of the driving task previously performed by the human driver. With partially automated vehicles (SAE level 2; SAE International 2018) already on the road today, both the longitudinal (e.g., adaptive cruise control) and lateral (e.g., lane keeping assist) control of the vehicle is being taken over by an ADS. Inevitably, this and future technology enabling higher levels of automation will cause out-of-the-loop problems (Kaber and Endsley 1997), mode confusion (Stanton and Marsden 1996), and behavioural adaptation (Rudin-Brown and Parker 2004) issues that need urgent reconsideration in order to maintain safe driving with automated vehicles (Navarro 2018; Saffarian, De Winter, and Happee 2012).

Most of these issues, such as those listed above, concern the stage where a transfer of control between the human driver and the ADS occurs. Therefore, the transfer of control from the human driver to the ADS, and vice versa, needs to follow a safe and meaningful process that circumvents or even solves the aforementioned issues. The concept of meaningful human control over automated systems is not new and was originally developed in the political debates on autonomous weapon systems (Article 36 2014). Ideally, a meaningful form of control should apply across all the forms of control (i.e., not solely operational, but also tactical and strategical; cf. Michon 1985) of a human being over an automated system. A recently developed philosophical account tried to spell out this idea in more detail, and defined two conditions that any system has to meet to allow for a meaningful form of human control. The first condition, 'tracking', regards the capacity of a system to always respond to human reasons to act or refrain from acting. In order to be under meaningful human control, a system should always be able to adjust its behaviour in accordance to a human controller's (or designer's) intentions. The second condition, 'tracing', prescribes the presence of at least one human agent (e.g., driver, operator, system designer, etc.) that can both (1) fully understand the real capabilities of the system and (2) wilfully bear the moral consequences of the system's behaviour (Santoni de Sio and Van de Hoven 2018).

The study of human behaviour in general is central to realise both conditions. For the tracking condition, investigating driver behaviour can substantially shed light on the extent to which a human driver or operator can—or should—express their reasons to act in relation to an ADS. For the tracing condition, behavioural science is important to determine the quality and quantity of the understanding required from a controller regarding the system's workings. In order to be able to attribute a meaningful form of control to a human driver—and thus a safer driving behaviour—it is therefore first necessary to assess what behaviour is involved in driving a vehicle (and with ADS), from a human-oriented perspective (Ranney 1994). Rasmussen's (1983) taxonomy distinguishes three levels of human behaviour (explained in more detail in Section 2.2) based on the assumption that humans are goal-oriented and thus not mere input–output systems that would structurally adhere to the commands given to them. This is compatible with the theoretical assumptions employed by the 'tracking' condition for meaningful human control. In fact, his theory prescribes that humans need *reason* (or *meaning*) for a given action, and thus could be used as a foundation for a human-oriented framework of meaningful human control over ADS.

This article aims to answer what (types of) human behaviour are involved in automated driving, and to what extent this behaviour gets affected by the introduction of ADS. Since a quantification of human behaviour with ADS is currently missing, in this article, a quantitative, rather than a qualitative, approach is taken. This approach, based on the analysis of literature, is assumed to provide detailed insights into the extent to which human behaviours play a role in achieving meaningful human control. The results from this study will serve as a foundation for further research into the applicability of meaningful human control over ADS.

2. Development of a framework of human control over automated driving systems

In this literature study, a framework of human control over ADS was developed by means of setting the taxonomy of the SAE related to on-road motor vehicle ADS (SAE International 2018) against the classification of human behaviour determined by Rasmussen (1983). This created a 6x3 framework, entailing 18 fields, of which each was filled by quantitatively assessing how many driving tasks are subject to each field. The quantitative assessment was performed through thorough literature research and, in several occasions for which literature not yet exists, inferential reasoning.

2.1. SAE levels of automation

The levels of automation set out by the SAE are divided into six categories, ranging from level 0 (no automation or manual driving) to level 5 (full automation). The SAE specifies that these levels are descriptive and technical, rather than normative and legal, meaning that they distinguish these levels by assessing what type of driving task is taken over by the ADS (e.g., if the execution of steering and acceleration/deceleration is being performed by the ADS, while the monitoring of the driving environment is still to be performed by the human driver, this ADS would be level 2 [partial automation]).

Specifically, the following definitions belong to the six levels of automation (SAE International 2018):

Level 0: 'The performance by the *driver* of the entire [*dynamic driving task*], even when enhanced by *active safety systems*'.

Level 1: 'The *sustained* and [*operational design domain*]-specific execution by a *driving automation system* of either the *lateral* or the *longitudinal vehicle motion control* subtask of the [dynamic driving task] (but not both simultaneously) with the expectation that the *driver* performs the remainder of the [*dynamic driving task*]'.

Level 2: 'The *sustained* and [*operational design domain*]-specific execution by a *driving automation system* of both the *lateral* and *longitudinal vehicle motion control* subtasks of the [*dynamic driving task*] with the expectation that the *driver* completes the [*object and event detection and response*] subtask and *supervises* the *driving automation system*'.

Level 3: 'The *sustained* and [*operational design domain*]-specific performance by an [*automated driving system*] of the entire [dynamic driving task] with the expectation that the [*dynamic driving task*] *fallback-ready user* is *receptive* to [*automated driving system*]-issued *requests to intervene*, as well as to [*dynamic driving task*] *performance-relevant system failures* in other *vehicle* systems, and will respond appropriately'.

Level 4: 'The *sustained* and [*operational design domain*]-specific performance by an [*automated driving system*] of the entire [*dynamic driving task*] and [*dynamic driving task*] *fallback* without any expectation that a *user* will respond to a *request to intervene*'.

Level 5: 'The *sustained* and unconditional (i.e., not [*operational design domain*]-specific) performance by an [*automated driving system*] of the entire [*dynamic driving task*] and [*dynamic driving task*] *fallback* without any expectation that a *user* will respond to a *request to intervene*'.

2.2. Classification of human behaviour (Rasmussen 1983)

In his paper, Rasmussen (1983) distinguishes between three types of human behaviour, namely skill-, rule- and knowledge-based behaviour. He defines skill-based behaviour as acts or activities which take place without conscious attention or control, and which is automated and highly integrated. Rule-based behaviour is defined as routinely executed acts or activities that follow a stored rule or procedure, often from instruction or preparation. The distinction from skill-based behaviour depends on the level of training and attention of the person, where skill-based behaviour is unconscious, and rule-based behaviour is consciously based on explicit recollection of facts. Knowledge-based behaviour is the performance of an act or activity during unfamiliar situations, and is goal-controlled. Here, a person needs to plan his/her actions, evaluate those, and consider the best response by functional reasoning. Usually, this is done by selecting from (parts of) previous similar experiences (and thus other rule- or skill-based behaviour), and piecing together a novel reaction to a novel situation.

2.3. Filling in the blanks: the baseline (SAE level 0)

To set a baseline for the set of skills, rules and knowledge required during (automated) driving, in this article we consider the case of a driver who recently successfully completed their basic driver training course in a European country. With regard to the choice of this baseline, rather than an 'ideal' or 'average' driver, we believe that these novice drivers are a reasonable baseline for this study, as they represent and express minimal requirements for being allowed to drive a regular vehicle, which would *theoretically* encompass all drivers' skill-, rule- and knowledge sets.

Therefore, we aimed to find a skillset, laid out by a European organisation, which is required to acquire a European driving license. This skillset is laid out by the CIECA Road Safety Charter working group's Harmonisation of the Assessment of Driving Test Candidates (CIECA Road Safety Charter Working Group 2006). This working group identified seven categories of driving skills necessary to pass a driving test, ranging from preparatory skills (e.g., checking the oil level and tyre pressure), via vehicle control (e.g., steering and accelerating/decelerating), to traffic adaptation skills (e.g., merging into traffic), each with their own (sub)categories. A total of 128 unique skills were extracted, which serve as the baseline for driver skill-based behaviour (see Table 1, top left field).

The baseline set of rule-based behaviour was derived from a 1968 convention on road traffic, during which the rules of the road were laid out to increase road safety throughout the European continent, commonly known as the Vienna Convention (United Nations 1968). In the Vienna Convention (United Nations 1968), 56 articles spread over six chapters discuss everything that enables safe driving in Europe. Excluding some exceptions that are for governmental bodies specifically, the contents of Chapter 2 to 5 are important for every driver to know, which describe the general rules of the road (Ch. 2), and vehicle- (Ch. 3),

Table 1. Framework of human control over automated driving systems.

		Automation					
		SAE 0	SAE 1	SAE 2	SAE 3	SAE 4	SAE 5
		No Automation	Driver Assistance	Partial Automation	Conditional Automation	High Automation	Full Automation
Human	Skill	128	127 – 114	114	114 – 43	40 – 0?	39 – 0?
	Rule	254	255 – 250	250	250 – 69* – 66	51 – 29?	29 – 0?
	Knowledge	65	65 – 81	81	81 – 34?!	0 – ?!	0?

The numbers represent the (range of the) total amount of behaviours that are expected from a novice driver to be present during the respective levels of vehicle automation.
[|]Fall-back to human up to SAE 3, means human needs at times adhere to SAE 0 levels.
[*]In case of accident; that is, in case the automation is *not* capable of avoiding an accident.
[?]Higher levels of automation involve unknown situations and definitions.
[!]Within this stage, driver skill- and rule-based behaviour may already deteriorate to knowledge-based, adding up to a driver's required knowledge-based behaviour.

driver- (Ch. 4) and cycle/moped condition requirements (Ch. 5). Furthermore, since 1968, two important changes have been made in light of the introduction of ADS, namely the inclusion of a new paragraph (5bis) in Article 8, and the amendment of Article 39 (United Nations 2014). These changes have been included in this article. In summary, the Vienna Convention lists a total of four chapters, in which 37 articles cover 151 main rules that are directly or indirectly related to motor vehicle drivers. In total, these 151 main rules cover 254 unique (sub)rules which form our rule-based behaviour baseline (see Table 1, middle left field). Examples of these rules range from general rules such as that one should not endanger or harm others, and that one should drive on the correct side of the road (left or right, depending on the country one is in), to more complex rules regarding the weight and dimension of goods one can load onto their vehicles, and registration and licensing rules.

2.3.1. The knowledge gap

The third and final step in setting the baseline was finding a set of knowledge-based behaviour for drivers who just received their license. This, however, proved to be challenging, as this entailed everything else that the sets of skills and rules haven't covered yet. Moreover, in search for such a set, the term 'knowledge' needed to be redefined in order to retrieve valuable information, since 'knowledge' as a key search term encompassed too many transient topics. As Rasmussen's (1983) definition states, this type of behaviour is related to unfamiliar situations, where the driver's behaviour is heavily dependent on the task-capability interaction (Fuller 2005), one can argue this type of behaviour is situationally induced behaviour (McKnight and Adams 1970). Therefore, we aimed to find a set of advanced driver training courses, as those courses aim at training unfamiliar situations. Unfortunately, no such set yet exists. However, some documentation reported advanced driver training courses from several selected countries in Europe (Lynam and Twisk 1995; SWOV 2009b). These documents served as a foundation for this part of the literature study. Each behaviour mentioned in these documents was listed, analysed for validity (i.e., is it not part of the basic skill or rule set), determined whether it had a correct order (i.e., whether it had to be further broken down into more specific types of behaviour), and checked if it is taught in advanced driver training courses in Europe, based on the references provided in the documents. In cases where a breakdown of behaviours was necessary, other sources were retrieved to validate these types of behaviour. Each reference cited and behaviour mentioned in these documents has been carefully studied, and their results have been summarised in Appendix (disregarding the results found from non-European countries; see Lynam and Twisk 1995[1]).

This approach resulted in a set which could be divided into four types of situationally induced behaviours, namely *roadway-*, *traffic-*, *environment-* and *car*-induced behaviours (McKnight and Adams 1970), supplemented with a fifth (human-oriented) category, namely *driver*-induced behaviour. This totalled 65 unique knowledge-based behaviours one may have to call upon during manual driving as a recently licensed car driver in Europe (see Table 1, bottom left field), such as identifying and recognising as well as handling under- or oversteer, predictive steering, and defensive driving techniques, such as reciprocation and joint-action.

2.4. Driver assistance (SAE level 1) and partial automation (SAE level 2)

After having set the baseline sets, the effects of the introduction of ADS to human behaviour were assessed. The amount of performed research regarding the effects of automation on driver skill is very limited (only research from Spulber 2016 and Young and Stanton 2007 were found that were somewhat related), as most research limits itself (understandably) to one or two individual skills like braking or steering. For rule-based behaviour, only the research by Vanholme et al. (2013) was found to be somewhat relevant for this study, so it appeared that a literature-based approach was not warranted hereon forward. Therefore, an inventory of all existing advanced driver assistance systems was sought, and a systems-based approach was taken. This inventory lists six systems that include either longitudinal or lateral assistance, ranging from antilock braking systems to automated parking assistance (Spulber 2016) (see also 'Which cars have self-driving features for 2017?' (2017) for a list per vehicle manufacturer). Further investigation found two more variations of such systems, thus totalling eight advanced driver assistance systems currently implemented in consumer market vehicles. Note that there are several more advanced driver assistance systems on the market (Wikipedia lists 31 as of September 2018), but these do not all perform 'the *driving mode* -specific execution […] of either steering or acceleration/deceleration using information about the driving environment' (SAE International 2018), but merely aid in either a part of that task (e.g., cruise control only maintains a steady speed, so it does not use information about the driving environment), or a different task (e.g., blind spot monitor, which warns the driver if there is something/someone in their blind spot) (see also 'Which cars have self-driving features for 2017?', 2017).

Inspection of the relevant systems regarding their impact on driver skill-, rule-, and knowledge-based behaviour based on the SAE definition showed that the amount of behaviours required from the driver differs depending on the system that is being used. For example, the autonomous emergency braking system only takes over the skill of performing an emergency braking procedure, whereas adaptive cruise control takes over the skill of braking smoothly when a car is in front of you, and several other skills involved in speed adaptation (see Young and Stanton 2007). Since the SAE defines level 1 systems to have *either* longitudinal *or* lateral control, the amount of skills required while driving with such a system is flexible. Because driving with advanced driver assistance systems is yet to be included within (European legislation for) basic driving courses, no added skills are foreseen as of yet (see Table 1, top second left field).

Regarding the amount of rules a driver needs to adhere to when driving with SAE level 1 systems, we consider the SAE definitions of the levels of automation as additional rules to adhere to. Further European legislation regarding ADS are—albeit under development—currently non-existent, although several separate European and non-European countries are progressively adapting rules regarding autonomous vehicles (see e.g., Wolfers 2017). Next to the additional SAE rules, again, depending on the system in use, varying amounts of rules are being taken over by the advanced driver assistance system. For example, a lane centring system needs to adhere to Article 10, rule 3, concerning the position within a lane, thus making it obsolete for the human driver to adhere to this rule (while driving with that system activated). Adaptive cruise control will, in its turn, need to adhere to Article 13, rule 2, regarding speed limits, and rule 5, regarding the distance between vehicles (see Vanholme et al. 2013). The results are presented at Table 1, middle second left field.

Lastly, the introduction of novel systems, such as advanced driver assistance systems, inadvertently introduces novel situations. Thus, in contrast with skill- and rule-based behaviour, these systems will *add* drivers knowledge-based behaviour more than they take over. Although little is known about what situations may occur when driving automated vehicles, several knowledge-based behaviours are expected to be requested by driving with such systems, such as coordinating, cooperating and collaborating with the activated system, but also understanding the distribution of tasks between the driver and the system, as well as knowing when it is safe to engage in secondary tasks (Spulber 2016). Most of these situations are thus concerned with the new supervisory task of the driver. Note that SAE level 1 systems could potentially take over some knowledge-based behaviour (i.e., a traction control system could take over advanced turn-negotiating techniques, albeit to a limited extent), but this does not outweigh the amount of additional knowledge-based behaviour introduced by these systems. Also note that, especially for novice drivers, the (negative) effect that driving with advanced driver assistance systems can have on human behaviour is not to be underestimated (see Tsapi 2015).

With SAE level 2 —or Partial Automation— systems, *both* longitudinal *and* lateral control is taken over by the ADS. This could potentially entail a vehicle that has adaptive cruise control with a lane-centring system, or a vehicle that has an automated parking system. Although somewhat dependent on the system, this basically entails that for the human driver the required amounts reach the maximum deviation from the baseline seen at SAE level 1 systems for both skill-, rule-, and knowledge-based behaviour (see Table 1, third left column).

2.5. Conditional automation (SAE level 3)

From the technical perspective of the SAE guidelines, a level 3 ADS entails a system that takes over *all* of the *dynamic driving task* within its *operational design domain*. This basically means that in the most extreme case all that is left for the human driver to do is to take the necessary preparatory measures before stepping into the vehicle, and drive off automatically. Therefore, regarding the required amount of skills while driving with a SAE level 3 ADS, a massive drop can be foreseen, as none of the skills trained during driver training are called upon, apart from, for example, being able to check the tyre tread and oil level, that the lights still work, and that the mirrors and windows are clean. The entire dynamic driving task, from changing gears to merging in traffic (cf. Young and Stanton 2007), will be performed by the ADS. However, since for instance driving in a traffic jam is also considered as an operational design domain for ADS of this level of automation (see SAE International 2018), this would essentially mean that the human driver may still need all the skills required while driving with level 2 systems.

Depending on its operational design domain, the same could apply to the amount of rules the human driver needs to adhere to. In the simplest domains (e.g., a closed off, designated area for the ADS solely, or during a traffic jam on a highway), the ADS would essentially only need to follow those rules that also apply to level 2 systems. However, if the operational design domain is extended to the more complex environments (e.g., urban areas, or shared spaces), many of the driving-related rules will have to be considered by the ADS instead of the human driver, such as the rules regarding overtaking, the priority rules, and rules regarding interaction with vulnerable road users. Nevertheless, a substantial amount of rules are left to the responsibility of the human driver. For example, rules regarding the registration, as well as the loading of your vehicle, and regarding the consequences of disobeying any rule, are still at the human driver's responsibility. Basically all rules that can be considered static throughout every drive. Notably, in the event of the vehicle getting involved in an accident—even though the system should be capable of avoiding accidents, as that is essentially part of the dynamic driving task—three rules regarding accident handling will apply to the human driver. Since the ADS should be designed to such an extent that an accident should not happen, this situation must be given special attention in the framework (see Table 1, asterisk sign).

When considering the amount of knowledge-based behaviour involved in driving with a SAE level 3 ADS, it becomes apparent that this introduces unknown situations to such an extent that quantifying the amount of knowledge-based behaviour required from a human driver becomes arbitrary (see Table 1, question mark sign). Nevertheless, an estimation has been made, based on the SAE's definition of level 3, of the consequences of the introduction of automation at SAE levels 1 and 2, and the consequences mentioned by Spulber (2016). Since, when deployed in an all-encompassing operational design domain, most knowledge regarding the dynamic driving task will become redundant at this level of automation—as the ADS now takes care of that—the amount of knowledge-based behaviour also declines. What remains are the knowledge-based behaviours regarding car-specific behaviours and understanding one's own behaviour whilst driving (with and without such an ADS). However, within this level of automation, one also has to consider the ironies of automation (Bainbridge 1983), one of which is the deterioration of (unused) skills and rules to a knowledge-based level (see Table 1, exclamation mark sign; see also Kaber and Endsley 1997; Navarro 2018; Spulber 2016). Moreover, as with the driver's skill- and rule-based behaviour, in a limited operational design domain such as a traffic jam, the same amount of knowledge-based behaviour as for level 2 may still be required.

Up to SAE level 3 automation, the SAE defines that the human driver is expected to serve as a fall-back to perform the dynamic driving task in case of an emergency, like a system malfunction (SAE International 2018) (see Table 1, bold line; see also 'Updated: Autonomous driving levels 0 to 5: Understanding the differences', 2016). This means that for all these levels (SAE levels 0 to 3), the human driver is expected to be able to perform as if they were driving a manual vehicle. Given the considered ironies of automation discussed above, this appears to be misplaced.

2.6. High automation (SAE level 4) and full automation (SAE level 5)

Beyond SAE level 3, where the human driver is still expected to act as a fall-back to safely control the vehicle in critical situations, most of the quantifications of human driver skill-, rule- and knowledge-based behaviour relies on speculation and debate. Where currently existing consumer vehicles with suggested SAE level 3 automation can achieve this level of autonomy only in very strict operational design domains, such as traffic jams—and thus not nearly encompass the entire domain SAE level 3 vehicles are expected to encompass—do consumer vehicles with SAE level 4 or 5 not exist at all ("Car autonomy levels explained" 2017). However, as with SAE level 3, certain assumptions can be made regarding a human driver's skill-, rule- and knowledge-based behaviour.

For example, it may be reasonable to assume that for a SAE level 4 ADS, the human driver will still be responsible for preparing their own vehicle before driving off, while on the other hand not expecting them to still remain in a driving position anymore, creating room for other activities, such as working on a laptop or reading a book, or even sleeping ("Drivers of BMW iNext will be able to sleep behind the wheel" 2017). Simultaneously, however, one has to wonder how much use a safety belt would still have under such circumstances, or whether people would still actually own their own vehicles, and thus whether or not they still need to be skilled in doing their own safety checks prior to their drive (Stocker and Shaheen 2017).

While for SAE level 3 ADS, the human driver still plays a key (fall-back) role within the driving task, with SAE level 4 ADS they can be taken completely out-of-the-loop. Therefore, certain human driver-oriented rules may not (need to) apply any longer, such as having a physically and mentally fit driver behind the steering wheel, potentially opening the way for disabled, children and the elderly to initiate a drive (Milakis, Van Arem, and Van Wee 2017). As with driver skill-based behaviour, it is however uncertain to what extent certain preparatory rules still apply (e.g., registration rules), while others are still likely to remain in place (e.g., loading rules). At full automation (SAE level 5), it is up to everyone's imagination as to what extent a 'driver' of such a vehicle still needs to abide to a (if any) rule (e.g., will "Don't litter" [Article 7, rule 2] be covered by a fully autonomous vehicle?).

Ultimately, knowledge-based behaviour is unlikely to be part of a driver's task demand while driving a SAE level 4 or 5 automated vehicle, but nevertheless certain situations may occur that places a driver in unknown territory, albeit hard to quantify.

3. Implications

3.1. The decline in skill- and rule-based behaviour

As can be seen in Table 1, a negative trend in the amount of required skills and rules coincide with the introduction of increasingly autonomous driving systems. With extended exposure to driving with such systems activated, the consensus is that an actual loss of skill can be expected (e.g., Bainbridge 1983; Navarro 2018; Parasuraman, Sheridan, and Wickens 2000; Young and Stanton 2007). Only by consistent maintenance of these skills and rehearsal of these rules, one could avoid having these deteriorate to a knowledge-based behaviour level (cf. exclamation mark sign at Table 1), but that requirement simultaneously beats the purpose of ADS altogether, as these systems—as goes for many other automated systems—are predominantly there to replace the human as the operator (Parasuraman and Riley 1997). Moreover, the way in which types of skills are being taken over (i.e., *qualitatively* speaking) is somewhat paradoxical, as at lower levels of automation these involve tasks a human driver can usually perform very well themselves (e.g., accelerating/decelerating), while the more difficult tasks are only included at higher levels of automation. In other words, while advanced driver assistance systems are supposed to *assist* drivers, they appear to often assist them with tasks they not necessarily need to be assisted in. This may explain the mixed feelings of people using them towards advanced driver assistance systems (Reagan, Kidd, and Cicchino 2017).

3.2. The rise and fall of knowledge-based behaviour

Contrary to the trend seen with skill- and rule-based behaviour, knowledge-based behaviour first experiences a rise in requests for the human driver. The introduction of advanced driver assistance systems appears to introduce more novel situations than they dissolve. Behavioural changes such as, but certainly not limited to, becoming complacent and having to supervise an automated system will have to be accounted for in order to ensure safe driving with such systems (e.g., Brookhuis, De Waard, and Janssen 2001; Lindgren and Chen 2007; Stanton and Young 2005).

Only during SAE level 3 automated driving we begin to see a decline in the request for knowledge-based behaviour, which is because of the execution of 'the entire dynamic driving task' by an ADS (SAE International, 2018). However, since the SAE also states that they have 'the expectation that the … [human driver] … will respond appropriately [to *requests to intervene*]', at least the behavioural changes mentioned above can be expected to become important to a driver's knowledge-based behaviour. To what extent a *request to intervene* requires knowledge-based behaviour is yet to be determined, but quick regeneration of awareness of the situation at hand is considered to be one of the requirements (e.g., De Waard et al. 1999; Eriksson and Stanton 2017; Lu, Coster, and De Winter 2017).

3.3. The human driver as a fall-back mechanism

As mentioned in Section 2.5, the human serving as a fall-back in case of an emergency appears misplaced. At the stage where a person has been driving with a SAE level 3 ADS for extended periods of time, reclaiming the control may be futile as the majority of skills, rules and knowledge necessary for safe driving have not been mobilised in this time (see Table 1). Especially when this level of automated driving encompasses novel techniques, such as platooning, more exacerbating behavioural adaptations may occur, such as carryover effects (Skottke et al. 2014), and loss of task engagement (Heikoop et al. 2017), to name a few. Given the fact that a deviation in skill-, rule- and knowledge-based behaviour from manual driving occurs throughout all levels of automation, it appears paramount to reconsider the driver's role as a fall-back mechanism during automated driving, especially when given the time to 'forget' about their learned skills and rules (see also e.g., Bainbridge 1983; Navarro 2018; Spulber 2016).

3.4. SAE level 4 and 5 automation: the path of the unknown

Consumer vehicles with SAE level 4 and 5 technology are currently only things of the future. Therefore, little knowledge exists on what the effects of those ADS would be on a human 'driver'. One thing is clear though, which is that a human will be completely removed from the driving task. Based on the framework presented in Table 1, we have to assume that at this stage, the driver is (almost) completely incapable of resuming manual control, so even a gradual decrease in the level of automation could potentially have hazardous consequences. From this, it appears that the fall-back threshold up to SAE level 3 (bold line at Table 1) has become a 'point-of-no-return', in the sense that manual intervention is not expected according to its SAE definition, but also not possible anymore, because of the issues mentioned in Section 3.3.

This does not mean, however, that while all of the dynamic driving tasks by the ADS are taken into account that we have created an infallible machine; system malfunctions can always happen, and a transition to lower levels of automation may (perhaps always) be expected at any given time and/or place. It also implies that new traffic and control situations that come with these new types of ADS have to be taken into account (cf. Table 1, two bottom right fields). To give the reader some examples of what might lie in the future in regard to autonomous driving, see Chipchase (2014) and Chipchase (2016), where '*car baiting*', '*modesty windows*' and '*juddering*' are described as future commonplace terms. Also tourism might get a whole different meaning, due to '*moving hotels*' and the '*reconceptualisation of the night-time*' (Cohen and Hopkins 2019).

One could also argue whether the extent to which the decline in skill- and rule-based behaviour is presented now in Table 1 will be accurate, since it can be expected that—similar to SAE level 3 automated vehicles on the market today—SAE level 4 and 5 vehicles may only operate in very strict operational design domains for the foreseeable future, limiting their effect on skill- and rule-based behaviour deterioration.

Lastly, regarding new legislation to be set out by European (or better yet: global) legislatorial bodies, the new situations that will arise also requires designs of novel legal safety systems. Some examples for applicable rules for the new type of driving with automated systems are suggested in Vanholme et al. (2013).

3.5. The 'Driver' component

When investigation the knowledge-based behaviours, it became apparent that although the roadway, traffic, environment and car are all important affecters of behaviour (McKnight and Adams 1970), a large proportion of this type of behaviour is directly dependent on the driver itself and its own acts and behaviours in traffic (see Appendix). A human-oriented "Driver" component was clearly missing for a complete classification of knowledge-based behaviour. Although the initial classification dates back to 1970, even today a twofold seminal question is repeated, namely whether Human Factors research is still failing to clasp on the rapidly developing automation industry, or whether Human Factors researchers will always be deemed to continuously warn us from making the same mistakes over and over again (Kyriakidis et al. 2017)? It is thus apparent that the human component in an obviously man-machine interaction-based domain is (still) being ignored, overlooked, or at least underestimated, even though it is an integral part of the core components of ADS

(Calvert, Heikoop, and Van Arem submitted). Given the heavy involvement of human-oriented behaviour—not limited to knowledge-based behaviour—this framework elicits, provides yet another case for the urge of Human Factors research in the ADS domain.

3.6. Implications for meaningful human control

The presented framework provides an assessment of the human component of the human–machine interaction with ADS, presenting a quantification of human behaviour in relation to driving tasks and levels of automation. Its contribution to the study of meaningful human control is twofold. Firstly, it helps in understanding the extent to which humans (driver, operators, etc.) are able to express certain reasons through behaviour. This understanding is of paramount importance in designing systems that are meant to respond to human reasons to remain under meaningful human control. Secondly, by providing an all-encompassing list of human behaviours during (automated) driving, the framework contributes to determine the extent to which humans can understand an ADS's mechanisms. This is vital to assess whether and to what extent the tracing condition is fulfilled, namely (in this case) whether some human driver/controller can legitimately be held responsible for the behaviour of the system, and is sufficiently aware and willing to endorse this responsibility. On the one hand, it is clear from the presented framework that the current transition of levels of automation does not fulfil the tracking condition, since the covariance between the human driver's intentions and the ADS behaviour is violated over the various levels of automation. Especially for SAE level 3 automation, the ADS requires more from the human driver than the human driver can intend, let alone perform. On the other hand, the framework clearly shows that in order for the tracing condition to be met, a transition of *responsibility* is required—rather than a transition of *control*—since with higher levels of automation it becomes more important how the ADS is designed to execute its tasks and less important how the human driver ought to execute its tasks. Since drivers' knowledge of the system and their capacity to perform tasks in general tend to decrease at higher levels of automation (see Table 1), other people ought to be considered more suitable to fulfil the tracing condition. Rather than the driver, designers or possibly control room operators might be good candidates for a meaningful role as controllers and thus bearers of (moral) responsibility.

4. Limitations, recommendations and future research

4.1. Limitations of this research

This research has aimed to develop a framework of human control over ADS by *quantitatively* assessing the effects various levels of automation have on human behaviour. This means that the framework presented in Table 1 does not provide answers about the effects on the *quality* of human behaviour. It can be argued that certain skill-, rule- or knowledge-based behaviours have more weight than others in the driving task.

Another limitation of this research is that, although a literature-based quantitative approach was attempted in this study, not all fields in the framework were viable for this approach, given the futuristic nature of the higher levels of automation (e.g., SAE level 4 and 5). The actual numbers may be different when actual SAE level 4 and 5 ADS exist.

A third limitation is that the framework is not empirically tested. Although validated by thorough literature research, empirical testing of the framework could provide more insights into its validity.

The final point of discussion that should be made here is that the adopted classification of human behaviour of Rasmussen (1983) is not the only suitable, nor necessarily the best classification that could be used for the development of such a framework. It is however a valid and suitable classification that allows the results from the presented analysis to taken at value. Examples of similar classifications of human behaviour are the Markov dynamic model of driver action (Pentland and Liu 1999), the conceptualisation of a driver's task (De Winter et al. 2014), the human-machine cooperation framework of Hoc, Young, and Blosseville (2009), or the hierarchical structure of the road user task (Michon 1985). Michon (1985) further summarises several more in-depth models of human behaviour (see also Heikoop et al. 2016; Stanton and Young 2000). Although the classification used in this paper provided valuable insights that could help increase safety in driving with ADS, we would encourage the construction of frameworks with different categorisations, as those could potentially highlight other bottlenecks and design issues related to human behaviour.

4.2. Mismatch between supply and demand

The developed framework sheds light on a serious problem with respect to the role a human driver is supposed to play within an ADS. At various levels of automation, large deviations from manual driving concerning skill-, rule- and knowledge-based behaviour raises issues regarding what human drivers can and still are required to do when driving (cf. Tsapi 2015). The apparent mismatch between the availability of skills, rules and knowledge at especially the higher levels of automation, and what is requested from the driver (e.g., acting as a fall-back) suggests that the current transfer of control within an ADS needs an overhaul, and, more importantly, a human-oriented transfer of control. A suggestion for this type of transfer would be a human-oriented approach, in which the ADS first takes over control of the tasks humans are notoriously bad at, such as parallel parking or reversing ("Mirror – Signal – Panic" 2018), and with higher levels of automation taking over progressively easier tasks. However, this elicits the paradox where the tasks that are difficult for human drivers to perform are difficult for an ADS designer to implement in its algorithms, which apparently calls for a change of perspective in the automation design domain.

Important to note is that the issue with the transfer of control is not only the mismatch between supply and demand, but also the possibility of mode error if this transfer is not communicated appropriately (Stanton and Marsden 1996).

4.3. Future research

The developed framework presented in this article suggests the need for a human-oriented taxonomy of levels of automation, in order to secure a safe and meaningful transfer of control. Future research should investigate how such a human-oriented taxonomy could look like. Next to empirically testing the validity of the framework presented here, it is suggested to empirically test any newly developed human-oriented taxonomy too.

Furthermore, predictive models like those used in economics or econometrics, or those used in the estimation of logistics- and fuel consumption benefits of platoons (see e.g., Janssen et al. 2015), could be used to attempt more sound calculations of the effects of the higher, futuristic, levels of automation. This extends to the many expected knock-on effects of vehicle automation on a traffic and infrastructural level, right up to the level of mobility patterns and choice by individual travellers as well as collectively. This will require greater insights into driver behaviour and models to scale-up these effects.

Lastly, a qualitative approach could be made regarding a framework that assesses the effects of automated driving on human behaviour that, for instance, adds weights to the specific tasks in relation to their importance or occurrence during driving with and without ADS, in order to assess for which tasks the most (qualitative) gain is to be made to automate, and to assess which tasks are most important to remain under human control to maintain meaningful human control over automated systems.

Note

1. Sources presented in Appendix can be from non-European countries, as often several techniques that are offered in advanced driver training courses (e.g., skid control) had to be dissected into specific behaviours (e.g., understeer and oversteer, etc.), which were sometimes validated through these non-European sources. Scientific references are therefore also the sources that provide a validation for this breakdown.

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Appendix

Overview of collected knowledge-based behaviours that are being taught in advanced driver training courses in various countries throughout Europe. The behaviours are categorised into the four types of induced behaviours, according to McKnight and Adams (1970), and a fifth, human-oriented, category. The respective sources are single examples that provide the specific (broken down) behaviours. Note that the source list is thus not the complete list used for the analysis of knowledge-based behaviour. All behaviours listed here are confirmed to be taught in advanced driver training courses throughout Europe (see Lynam and Twisk1995; SWOV2009b).

Category	Knowledge-based behaviour	Source
Roadway-induced behaviours	Accelerating out of curve	https://driving-tests.org/beginner-drivers/killer-curves-how-to-stay-safe-while-driving-on-curvy-roads/
	Anticipating at amber phase (approaching, braking, looking)	http://www.cfc.lu/pages/english/courses/professional-and-vip-driver.php
	Cross viewing	http://approved-driving-instructor-training.co.uk/adi-part-2/advanced-observations/
	Curve approaching	https://driving-tests.org/beginner-drivers/killer-curves-how-to-stay-safe-while-driving-on-curvy-roads/
	Mirrored steering	https://www.iam-bristol.org.uk/index.php/articles/associate-s-guide/59-mirrored-steering
	Negotiating curves and turns	https://www.tecnic.ca/en/business-services/defensive-driving-on-slippery-surfaces
	Obstacle avoidance (steering vs braking)	Adams (1998)
	Predictive steering	http://trackpedia.winhpde.com/wiki/Steering_techniques#Predictive_Steering
	Reading the road	http://approved-driving-instructor-training.co.uk/adi-part-2/advanced-observations/
	Slowing down during curves	https://driving-tests.org/beginner-drivers/killer-curves-how-to-stay-safe-while-driving-on-curvy-roads/
	Understanding the dangers of curvy roads	https://driving-tests.org/beginner-drivers/killer-curves-how-to-stay-safe-while-driving-on-curvy-roads/
Traffic-induced behaviours	Being aware of drivers who don't stay in their lane (during rush hour)	https://www.nsc.org/road-safety/safety-topics/night-driving
	Dealing with impaired drivers	https://www.nsc.org/road-safety/safety-topics/night-driving
	Identifying distant traffic hazards	Brown and Groeger (1988)
	Interpreting the actions of others	Swan and Owens (1988)
	Looking away from oncoming lights during night time driving	https://www.nsc.org/road-safety/safety-topics/night-driving
	Perceiving information regarding the potential hazards in the traffic environment	Brown and Groeger (1988)
	Quantification of the potential for danger	Brown and Groeger (1988)
	Reciprocating on the actions of others	Swan and Owens (1988)
	Staying in your lane (during rush hour)	https://www.nsc.org/road-safety/safety-topics/night-driving
	Taking note of the action of others as indications are made (joint-action)	Swan and Owens (1988)
Environmentally induced behaviours	Aiming headlights correctly for night time driving	https://www.nsc.org/road-safety/safety-topics/night-driving
	Dealing with and becoming aware of microclimates (essential on rural roads in the winter!)	https://www.driversdomainuk.com/multiple-drivers/
	Dimming dashboard during night time driving	https://www.nsc.org/road-safety/safety-topics/night-driving
	Knowing how to drive during winter	https://www.tecnic.ca/en/business-services/defensive-driving-on-slippery-surfaces
	Knowing the adverse weather conditions that can occur during seasons	https://www.tecnic.ca/en/business-services/defensive-driving-on-slippery-surfaces
	Understanding the influence of speed and reaction time	http://www.cfc.lu/pages/english/obligatory-courses/car-cat.b.php
	Understanding zones of visibility	https://www.driversdomainuk.com/multiple-drivers/

Car-induced behaviours	Dual-movement steering	https://www.rac.co.uk/forum/showthread.php?9251-Guide-for-steering-techniques
	Eco driving	https://www.prodrivetraining.nl/defensive-driving
	Fixed-input steering	https://www.rac.co.uk/forum/showthread.php?9251-Guide-for-steering-techniques
	Having correct position at wheel (for skid control)	https://www.tecnic.ca/en/business-services/defensive-driving-on-slippery-surfaces
	Knowing how to brake (during skidding)	https://www.tecnic.ca/en/business-services/defensive-driving-on-slippery-surfaces
	Knowing skidding types depending on the vehicle type	https://www.tecnic.ca/en/business-services/defensive-driving-on-slippery-surfaces
	Learning how to identify and recognise an oversteer skid	https://lincsdrivingsolutions.uk/skid-control-training/
	Learning how to identify and recognise an understeer skid	https://lincsdrivingsolutions.uk/skid-control-training/
	Learning how to recover from both understeer and oversteer skids	https://lincsdrivingsolutions.uk/skid-control-training/
	Palming (steering technique)	https://www.rac.co.uk/forum/showthread.php?9251-Guide-for-steering-techniques
	Perceiving information on the capabilities of the vehicle to prevent potential hazards from being transformed into actual accidents	Brown and Groeger (1988)
	Pull steering	https://www.rac.co.uk/forum/showthread.php?9251-Guide-for-steering-techniques
	Push and control steering	https://www.rac.co.uk/forum/showthread.php?9251-Guide-for-steering-techniques
	Understanding about the balance and physics of a vehicle	https://lincsdrivingsolutions.uk/skid-control-training/
	Understanding how Anti-lock braking and Electronic Stability Programmes work	https://lincsdrivingsolutions.uk/skid-control-training/
	Understanding the forces with a collision	Nyberg and Engström (1999)
Driver-induced behaviour	Calibration	International Road Federation Road Safety Committee (2014)
	Consulting a map and familiarise yourself with/memorise the route for night time driving	https://www.nsc.org/road-safety/safety-topics/night-driving
	Driving slower during night time driving	https://www.nsc.org/road-safety/safety-topics/night-driving
	Getting appropriate amount of sleep for night time driving	https://www.nsc.org/road-safety/safety-topics/night-driving
	Handling/Avoiding road rage	https://www.driversdomainuk.com/multiple-drivers/
	Having anti-reflective glasses for night time driving	https://www.nsc.org/road-safety/safety-topics/night-driving
	Knowing how to make observational links between what is seen on the road and required driver response	https://www.driversdomainuk.com/multiple-drivers/
	Minimising distractions during night time driving	https://www.nsc.org/road-safety/safety-topics/night-driving
	Minimising risks when being late	https://www.thinkingdriver.com/hazard-avoidance-training
	Not going on auto-pilot during night time driving	https://www.nsc.org/road-safety/safety-topics/night-driving
	Perceiving information on the ability of the driver to prevent potential hazards from being transformed into actual accidents	Brown and Groeger (1988)
	Pulling over when drowsy during night time driving	https://www.nsc.org/road-safety/safety-topics/night-driving
	Resting every 2 hours during night time driving	https://www.nsc.org/road-safety/safety-topics/night-driving
	Traveling during times you are normally awake for night time driving	https://www.nsc.org/road-safety/safety-topics/night-driving
	Understanding causes of road rage	https://www.driversdomainuk.com/multiple-drivers/
	Understanding courtesy signals	https://www.driversdomainuk.com/multiple-drivers/
	Understanding own behaviour	Keskinen et al. (1999)
	Understanding own limitations	Gregersen (1999)
	Understanding own responsibilities	Lynam and Twisk (1995)
	Understanding the effects of alcohol	http://www.autorijschoolalkema.nl/alcoholvrij%20wat.htm