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A state of science on highly automated driving

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ABSTRACT

Technological improvements have made highly automated driving (HAD) a reality. The aims of the current contribution are to (1) clarify concepts related to vehicle automation and associated human–machine cooperation issues, (2) summarise research directions that have already been explored with HAD, (3) summarise known effects of HAD on humans' cognitive functions and constructs, (4) discuss current and future issues and challenges for vehicle automation, and (5) extend the debate to the design and use of human tools. Both theoretical and practical insights indicate that HAD is deeply modifying drivers' activity and could result in safety-critical difficulties for drivers under certain circumstances. Attentional processes, workload, situation awareness, behavioural adaptations, the out-of-the-loop phenomenon, acceptance of and trust in automation are the main cognitive dimensions and constructs investigated in order to describe how HAD is impacting driving. Future research directions that may help improve HAD are discussed. Finally, the fact that human tools both result from but simultaneously go beyond individual intelligence is described as the new irony of automation.

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Car driving; automation; human–machine cooperation; automated driving; highly automated driving

Relevance to human factors/ergonomics theory

Ever-increasing driving automation is deeply modifying drivers' activity and their relationships with automation. This paper aims to present an overview of the human–machine cooperation issues associated with highly automated vehicles from both theoretical and empirical perspectives. Future research directions are proposed to improve human–machine cooperation with highly automated vehicles.

1. Context

Vehicle automation is currently an important issue in modern societies with ever-increasing automation devices available. In addition to the technological challenges associated with the practical implementation of vehicle automation, the way in which these automated solutions are used by humans is also a major issue. The analysis and optimisation of the relationships between humans and automation traditionally fall within the scope of cognitive ergonomics (e.g. Bainbridge 1983; Hollnagel and Woods 1983; Parasuraman and Riley 1997; Rasmussen 1974). Technological developments and the level of

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automation escalation they bring represent a constant challenge to ergonomists regarding the nature and quality of human–machine interactions (HMIs). Machine capabilities have reached such a level that the term human–machine cooperation (HMC) might now be a more accurate way of describing the way humans and automation interact, particularly in highly complex and dynamic human–machine systems (Hoc 2000, 2001). Car driving is a common complex and dynamic situation, which makes vehicle automation a situation well suited for HMC analysis and optimisation (Hoc, Young, and Blosseville 2009; Navarro 2017; Navarro, Mars, and Young 2011). This explains why vehicle technology has been a major object of publications in the human factors/ergonomics community ever since the end of the twentieth century (Lee 2008).

The prospect of self-driving cars is coming ever closer. Some researchers predict that fully automated vehicles may be present on the roads by 2030 (e.g. Walker, Stanton, and Young 2001) and a number of car manufacturers have officially reported that they are actively working on fully automated vehicles (e.g. General Motors, Mercedes, Nissan, Volvo). Nissan motor company CEO Carlos Ghosn said 'Now I am committing to be ready to introduce a new ground-breaking technology, Autonomous Drive, by 2020, and we are on track to realize it' (Nissan Motor Compagny 2013). While the timeframe for implementation differs depending on the sources and year of prediction, there is a universal consensus that full driving automation is on the horizon. Does this mean that drivers will have no further role to play in driving? Possibly in the distant future. However, the technology for completely autonomous vehicles is not yet available. As an example, a recent demonstration during CES 2017 in a simple environment failed to prove conclusive even for a basic self-parking manoeuver (Murphy 2017). The truth is then that drivers will continue to play a role for some time to come.

The form of automation made possible by today's technology is referred as highly automated driving (HAD). In HAD, drivers are not expected to control the vehicle speed and steering continuously. However, they are still expected to regain manual control occasionally when the automation solution reaches its limits or in the case of a malfunction. Consequently, drivers remain the agents of last resort who are in charge of the situation. It is therefore interesting to consider the impacts of HAD on drivers' behaviours. Are highly automated vehicles always of benefit to drivers? What are the known consequences of HAD on drivers' behaviours and cognitive processes?

Within this context, the purpose of the current contribution is to (1) clarify the concepts related to vehicle automation and associated HMC issues, (2) summarise research directions that have already been explored in the HAD field, (3) summarise the known effects of HAD on humans' cognitive functions and constructs, and (4) discuss current and future issues and challenges. Each of these objectives is pursued in a specific section. Section 2 aims at quantifying the number of researches devoted to HAD over time, define HAD through the main driving automation classifications and to position HAD compared to other automation in terms of LOA and HMC intensity. Sections 3 and 4 present a synthesis of the literature. Section 3 offers a synthesis of empirical works associated to HAD. The available data were organised in four sections: (1) when the driver supervise the machine with HAD operating, (2) when the driver has to regain control from automation, or (3) leave control to automation and (4) HAD after-effects on manual driving. Section 4 synthetises the cognitive dimensions and constructs addressed in the literature regrouped in five categories: (1) attention, distraction and fatigue, (2) workload and situation awareness, (3) behavioural adaptations (BAs) and out-of-the-loop, (4) trust and (5) acceptance. Section 5 offers an overview of the reported results and discusses future research directions to further improve HMC in highly automated environments.

2. Concept and definition

2.1. Number of researches dedicated to highly automated driving over time

Research interest in vehicle automation, and HAD in particular, is currently growing. Table 1 presents the results, classified decade-by-decade, of a Google Scholar search including international books, journals and conference proceedings but excluding patents and citations. The number of contributions dedicated to HAD has increased exponentially since the 1990s. The search found more than a hundred contributions since 2010, with about three years still to go in this decade, compared to only one contribution in the 1990s and three in the 2000s. These hits have been classified at a general level depending on the nature of the contribution. More than half are associated with ergonomics/human factors (55.8%) and about 40% are associated with the scientific aspects of automation. Contributions are therefore fairly evenly balanced between these two fields. The general increase in the number of hits partly reflects the expansion of the database in recent years. To take this more exhaustive coverage into account, we calculated the number of hits for 'highly automated driving' as a proportion of the number of hits collected for the terms 'driving' AND ('vehicle' OR 'car' OR 'transportation'). The contributions relating to HAD account for about 5% of all driving-related contributions since 2010, whereas the corresponding figure was very close to zero during the previous two decades.

2.2. Automation-based classifications

Despite the number of HAD contributions related to ergonomics and human factors (see Table 1), automation design is still mostly guided by technological possibilities. Indeed, the three most influential international vehicle automation classification systems are based on the functional aspects of technology. The human (i.e. the driver) is only considered as the agent in charge of those functions that technology has not automated or, in the last resort, when automation is unavailable or fails to perform its task. These three classification systems, developed namely by the German Federal Highway Research Institute (BASt, Gasser and Westhoff 2012), the Society of Automotive Engineers (SAE

Table 1. Number of hits in Google Scholar resulting from a decade-by-decade search for the term 'highly automated driving' classified into broad research areas, and compared to hits for the term 'driving' (in combination with the words 'vehicle', 'car' or 'transportation').

	Highly automated driving (HAD)		
	1990s	2000s	2010s
Ergonomics/human factors	1	3	57
Automation science			40
Others			5
Total	1	3	102
Driving AND vehicle OR car OR transportation	378	1190	2210
HAD/driving	0.003	0.003	0.046

international 2014) and NHTSA (National Highway Traffic Safety Administration (NHTSA) 2013) are in line with the seminal work on Levels Of Automation that described automation tasks in terms of capabilities (LOA, Sheridan and Verplank 1978). From a general perspective, these three classification systems are all very consistent with one another because they are constructed on the basis of the same criteria: firstly, the automated tasks, followed by the automation capabilities and failure management. The main common classification criterion is the type and number of automated driving subtasks (e.g. speed control and/or lateral control). Next, automation capabilities are considered in terms of the automation validity domain (i.e. the environmental contexts in which automation is expected to work properly). Finally, although the last criterion involves drivers, it simply describes whether they are expected to take over the driving tasks in case of an automation failure. In sum, these classifications are a good description of what automation is capable of, but provide no insights into drivers' and HMC activities (see Navarro 2017 for more details).

In all three classifications, HAD is classified as the level immediately below the fully automated vehicle in terms of LOA. HAD is divided into three distinct levels in the SAE classification: level 4 if the driver is not expected to handle the driving tasks even in case of an automation failure, level 3 if the driver is expected to handle driving in case of an automation failure and level 2 if the driver is excepted to monitor the driving environment (SAE international 2014). Whatever the classification considered, HAD tends to 'replace' rather than to 'support' drivers according to Stanton and Young terminology (1998). Thus, HAD manages both speed and lateral control, previously handled by drivers, at least under some circumstances and for a certain amount of time.

2.3. Automation and human-based classifications

One well-known attempt to improve our understanding of the relationship between humans and automation was made by crossing a simple four-stage model of human information processing with the LOA (Parasuraman 2000; Parasuraman, Sheridan, and Wickens 2000). The levels of automation are directly inspired by Sheridan's stepwise LOA hierarchy, from no automation to automation that acts autonomously and completely ignores the human actor (Sheridan and Verplank 1978). LOA is considered separately at the four stages of human information processing. The levels of automation are therefore described at the stages of (1) information acquisition, (2) information analysis, (3) decision selection and (4) action implementation. The combination of stages and levels of automation makes it possible to describe the impact of automation in parallel with the main human processing steps, with the result that a given type of automation may be associated with different LOA depending on the processing stage considered. Figure 1 represents the LOA at the four stages for the main vehicle automation devices as compared with no automation. Excluding warning automation, which constitutes a different LOA depending on the stage considered, haptic shared control, HAD and fully automated driving (FAD) all constitute a consistent LOA across all four stages (Figure 1). The LOA increases in linear form from no automation to FAD, while passing through warnings, haptic shared control and HAD in that order. The output from this model provides a qualitative description of HMIs, but does not describe the cognitive mechanisms behind these interactions.

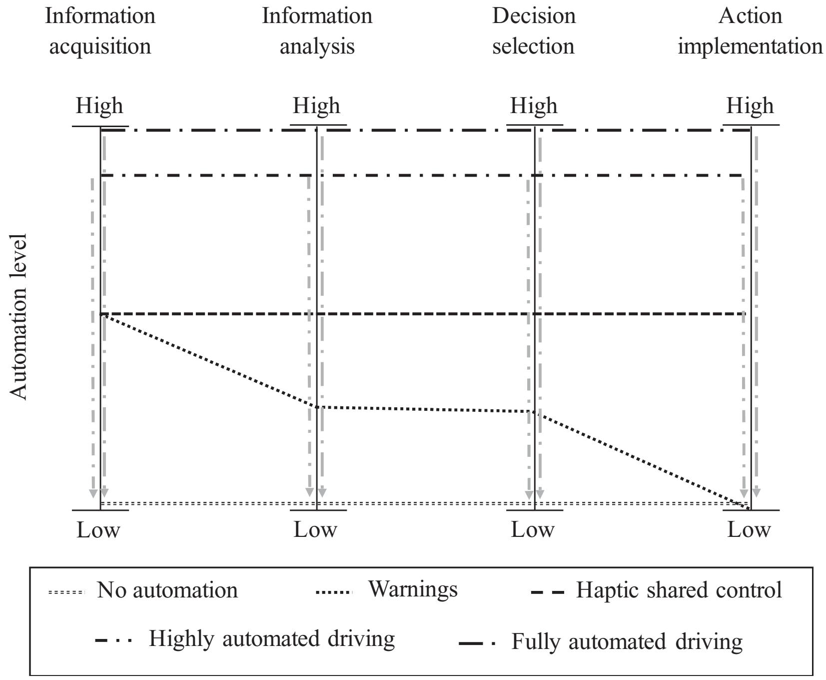

Figure 1. Stages (from information acquisition to action implementation) and levels (from low to high) of automation for no automation and the four main driving automation devices (Parasuraman et al. 2000). The light grey zone represents the hazardous zone corresponding to the case of automation failure. The vertical grey arrows represent the changeovers from automation to manual control required in case of a failure of high or full automation.

2.4. Human–machine-based classifications

Other HMC models make it possible to classify automation devices in the light not only of the capabilities of the machine and the human agent but also of their interactions (Hoc, Young, and Blosseville 2009; Navarro 2017; Navarro, Mars, and Young 2011). To qualify HMIs, referred to as interferences, these models introduce the concept of HMC modes. Each cooperation mode qualifies the operational control between humans and automation and associated interferences. As far as car driving is concerned, five main HMC modes, classified on the dimensions of 'vehicle automation' and 'driving automation', have been described (Navarro 2017; Navarro, Mars, and Young 2011).

At the level of vehicle automation, a single *integrated mode* exists. Here, driver assistance systems are considered as part of the vehicle properties (Young, Stanton, and Harris 2007). HMC is therefore very limited and the most the driver can do is to choose whether or not to enable the device, as in the case of an electronic stability program (ESP) for instance. Some vehicle automation devices have reached such a level of integration that the driver has no choice but to accept them, as in the case of the antilock braking system (ABS) that is present in most vehicles. It should be noted that drivers are not fully aware of automated actions and they may even be unaware of the presence of automation devices in their vehicles (e.g. Braitman et al. 2010; Robinson et al. 2011).

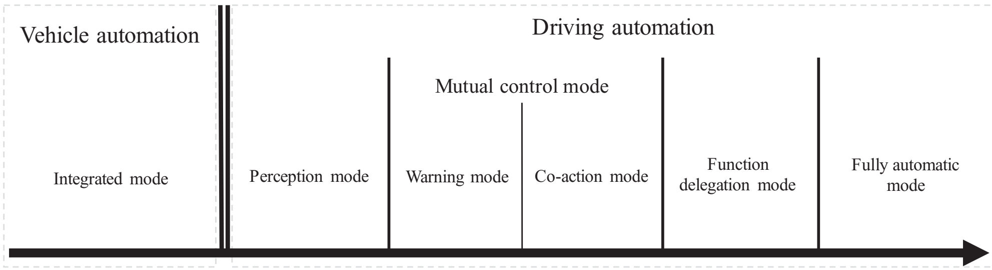

Figure 2. Human–machine cooperation modes. Adapted from Navarro et al. (2011).

At the next level, the HMC modes belong to the driving automation category and are subdivided into four main forms of HMC (Figure 2). With the *perception mode*, automation extends/enhances drivers' capabilities (e.g. speedometer for speed assessment). In this HMC mode, the critical automation design questions relate to the way the information is displayed (e.g. Dijksterhuis et al. 2012; François et al. 2017; Lorenz, Kerschbaum, and Schumann 2014). Even if the information displayed can be more or less salient and relevant, drivers initiate the use of the device and the related human–machine interferences. The task of the automation device is to enhance drivers' capabilities if deemed useful by the drivers themselves.

Within the second driving automation HMC mode, referred as *mutual control*, the human and the machine are both performing the same task in parallel. If the device simply warns drivers in a variety of situations, as in the case of forward collision warning systems (e.g. Lee et al. 2002) or lane departure warning systems (e.g. Navarro et al. 2017), (e.g. Navarro et al. 2017) they constitute a 'warning mode'. Automation can also directly act on vehicle control, as in the case of haptic shared control (e.g. Griffiths and Gillespie 2005; Mulder, Abbink, and Boer 2012), and could therefore be referred to as a 'co-action mode', since the driver and automation solution act jointly to physically control the vehicle (see also Brangier and Hammes-Adelé 2011 for a co-action definition). Mutual control assistance devices are more intrusive than those involved in perception mode, and human–machine interferences are triggered by the automation solution in response to driver behaviour. Human–machine interferences are more frequent in co-action mode (continuous co-action) than in warning mode (temporary automation interference). HMC is therefore more intense in mutual control mode than in perception mode.

The third HMC mode involved in driving automation is referred to as *function delegation*. Here, drivers decide to delegate some of the driving tasks to automation (e.g. adaptive cruise control – ACC – for longitudinal control or automatic steering – AS – for lateral control). The nature of the HM interferences is greatly changed as automation is now primarily responsible for control of the delegated task and the driver is expected to supervise the automated actions. The frequency of HM interferences is restricted to the supervision of automatic actions and to the decision to delegate and regain manual control whenever this is desirable or necessary. With only some aspects of vehicle control being delegated to automation, drivers continue to be responsible for the other driving tasks. This means that they have to take account of the outcomes of the delegated function when exercising manual control of non-delegated driving tasks. For instance, if longitudinal control is delegated to an assistance device (ACC), drivers must steer the vehicle in the light of the automatically adjusted speed of travel.

The last HMC mode involved in driving automation is a *fully automatic mode* in which all the driving tasks are delegated to automation. At this level of automation, the HM interferences would be reduced to the choice of destination and, to a certain extent, the supervision of the automated activities (e.g. check for planned arrival time).

2.5. The relationship between levels of automation and human–machine cooperation intensity

2.5.1. Description

Figure 3 presents a diagrammatic representation of driving automation devices relative to the associated LOA, HMC modes and the intensity of the HMC. This integrative perspective constitutes a new matrix of human–machine relationships. Using the traditional LOA description, the more sophisticated the technology is and the more involved it is in task control, the higher the level of automation. Without automation, the LOA is extremely low and it increases in a linear fashion to become extremely high with full automation. Different automation devices have been placed along these start and end points (circles along the dotted grey arrow in Figure 3). Simple warnings support drivers at a lower LOA than action suggestion devices (e.g. Navarro et al. 2010; Navarro, Mars, and Hoc 2007 for lateral control), which act at a lower LOA than haptic shared control devices that play a larger role in task control. In turn, haptic shared control represents a lower LOA than ACC and AS. Finally, HAD and FAD are the most advanced automation levels and

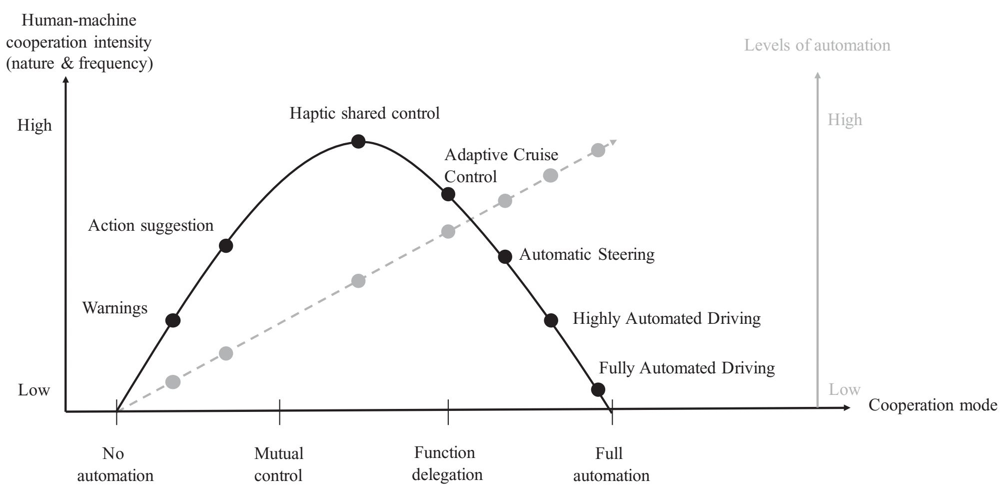

Figure 3. Different types of driving assistance classified along the dimensions of human–machine cooperation intensity, levels of automation and cooperation mode. The dotted grey arrow represents the usual increase in the description of automation in terms of low to high LOA (based on Sheridan and Verplank 1978 initial description). The cooperation modes represent the level of intervention by the automation device in terms of human–machine cooperation (based on Hoc et al. 2009; Navarro et al. 2011). The inverted U-shaped curve describes the intensity of human–machine cooperation from low to high. The points indicate the relative position of different automation devices relative to both the LOA scale (in grey) and the human–machine cooperation intensity scale (in black).

provide the highest LOA. Although they describe HMC, the cooperation modes (Hoc, Young, and Blosseville 2009; Navarro, Mars, and Young 2011) support this idea of an increase in automation since operational control and the related HM interferences are directly dependent on the intervention of automation during task control.

Human–machine cooperation intensity (HMCI), which is defined in terms of the nature and frequency of HMC, does not increase linearly in the same way but instead follows an inverted U-shaped curve. Seen in this light, warnings provide a fairly low HMCI due to the negative feedback implied by such devices and the temporary nature of the interference resulting from them. Indeed, warnings constitute a criticism of driver behaviour when certain circumstances occur. This is a fairly infrequent situation. Although not more frequent, the HMCI is greater in the case of devices that suggest an action in addition to issuing a warning, since the nature of the interferences is different. Automation interferes not only with the diagnosis of the situation but also with the preparation for action by suggesting the action that the driver should perform. The most intense HMC interferences are reached with haptic shared control, with which the human and the machine continuously share both the environmental analysis and the control of action. Then, and contrary to the constantly increasing sophistication of automation solutions and their level of task involvement, HMCI decreases. With ACC, this decline is small since drivers are still in charge of steering, i.e. the main activity involved in vehicle control. Interferences with ACC are not uninterrupted in terms of action control and the supervision of automated responses. The decrease in HMCI is greater in the case of AS, given that steering is the core activity of vehicle control and is known to be closer to HAD than longitudinal control (Carsten et al. 2012). HMCI is even weaker with HAD as both longitudinal and lateral control are delegated to automation. Finally, the weakest HMCI is observed with FAD – a situation in which drivers no longer do any driving.

2.5.2. Impact on performances

With HAD, currently the smartest form of artificial intelligence, it is surprising to observe that the HMCI is low compared to the high LOA situations. This association between a high LOA and a low HMCI may explain the difficulties faced by drivers while interacting with HAD (as exemplified in two journal special numbers on HAD: Merat and de Waard 2014; Merat and Lee 2012). Due to the low HMCI, drivers are not ready to regain manual control if required. This description of HMCI fills the gap illustrated in Figure 1 by the grey vertical dotted arrows at the point of transition from automated to manual control. The amplitude of the transition on the LOA scale required in order to regain manual control is very important (Figure 1). Moreover, the weak HMCI in the case of HAD may make it more difficult for drivers to regain manual control (Figure 3). In HAD, the HMCI is equivalent to that observed with simple warning devices. To a certain extent, HM interferences for both warnings and HAD are comparable. With warnings, the automation solution supervises drivers and only intervenes when their behaviours are judged inappropriate. The reverse is true in the case of HAD, i.e. drivers supervise the automation solution and only intervene when the automated actions are judged inappropriate. Although similar at the level of HMC intensity, there are several differences between warnings and HAD in terms of control, authority, responsibility and ability as defined by Flemisch et al. (2012).

Table 2. Distribution of activities between human (H) and machine (M) for the four cornerstone concepts of human–machine cooperation described by Flemisch et al. (2012) as a function of the automation device considered, the human–machine cooperation mode and the level of driving automation following the SAE classification (SAE International 2014).

SAE level	Cooperation mode	Automation device	Control	Authority	Responsibility	Ability	Development of drivers' skills
0	No cooperation	Manual driving	H	H	H	H	Skills reinforcement
	Mutual control	Warnings	H + m	H	H	H + m	Skills reinforcement & adjustments
		Haptic shared control	H + M	H + M	H	H + M	Skills reinforcement & adjustments
1	Function delegation	Adaptive cruise control or automatic steering	H + m	H + m	H	H + m	Skills maintained
2		Highly automated driving	H + M	H + m	H	H +M	Skills decline
3			M + h	M + h	H + m	M + h	Skills loss
4			M + h	M + h	M + h	M + h	Major skills loss
5	Full automation	Fully automated driving	M	M	M	M	Skills disappearance

Note: Capital letters (H and M) are used for the main agent or when both agents' contributions are equivalent. Lower-case letters (h and m) are used for the secondary agent if necessary. The impact of the automation device on the development of drivers' ability is also presented in the last column.

2.5.3. Impact on control, authority, responsibility and ability concepts

Table 2 summarises the contributions made by humans and machines to the four cornerstone concepts underlying HMC and the development of drivers' abilities. Under *manual driving* the human has the control, ability, authority and responsibility of driving. Driving skills are reinforced by manual driving practice. Even in the presence of automated warnings, the human remains the main agent for all four HMC cornerstone concepts but is nevertheless supported by the machine at the levels of control and ability. Here, the machine is involved in the perception loop and has the ability to notify situations judged as unsafe to the driver. Such automation devices make it possible to reinforce and even improve drivers' skills (e.g. Navarro et al. 2016). With *haptic shared control*, although the human and the machine share control, authority and ability equally, the human remains the agent responsible for the global outcome. With *ACC* or *AS*, the human remains the primary control agent assisted by the machine for lateral or longitudinal control. Authority is mainly attributed to the human that can delegate part of it to the machine. The human ability and skills are preserved as only part of control is delegated. The machine also has the ability to manage either lateral or longitudinal control. As previously exposed, three SAE levels (levels 2, 3 and 4; SAE International 2014) correspond to *HAD*. At SAE level 2, the machine primarily assumes vehicle control, but the human is still expected to monitor the driving environment. The machine has the authority to control the vehicle under certain situations but the human has the authority to regain control (i.e. control change authority) and outside the situations managed by the machine. The human remains responsible but skills decline is excepted as the ability is shared with the machine over time. At SAE level 3, the human still assume most of the responsibility (the machine has limited responsibility under nominal conditions) but acts as a secondary agent in terms of control, authority and ability. In the long term, this could result in a loss of skills. The machine assumes primary vehicle control and has the authority (i.e. authority to control and change control of the vehicle in the case of disengagement) and ability to do so. However, the human has the authority to regain control (i.e. authority to change control). In such cases, the human then temporarily controls the vehicle. It is therefore necessary that humans maintain the ability to do so. At SAE level 4, the machine is the primary agent for all four dimensions with the human allowed to regain control under given circumstances, having the authority and being responsible to do so. Human interventions are dramatically reduced and optional, thus major skills loss could be expected. With *FAD*, the machine appropriates all four concepts and human driving skills would be expected to disappear in the long term.

Overall, in HAD the machine is the main agent in the human–machine team in terms of control, authority and ability but the human still assumes most of the responsibility. Except at level 4 of the SAE classification, the human remains responsible for the general human–machine team outcome and must (1) concede control or decide to return to manual control, (2) concede authority or decide to regain authority and (3) maintain driving skills without practice. Thus, in theory, this role distribution between the human and the machine is a source of difficulties for the human. The aim of the next two sections is to report the main practical research results related to HAD use.

3. Issues investigated

3.1. Methodology

All the articles available in the literature and associated to HAD related to ergonomics/human factors (see Section 2.1) were considered for inclusion. Only articles presenting empirical data were included. The same corpus of papers was used for Section 3 and Section 4. In Section 3, the focus was placed on automation impact on driver's behaviours, whereas Section 4 focused on the underling cognitive mechanisms. The heart of this literature review is on HAD, a situation in which both lateral and longitudinal control are operated by automation, at least under certain circumstances. To increase the corpus of peer-reviewed journal articles, we also considered the two most similar types of automation in terms of both LOA and HMCI (namely: AS and FAD, Figure 3) in addition to articles relating to HAD. Studies containing data on ACC are not systematically reported below but mentioned as a reference point when deemed useful. Most of the studies available in the literature were carried out on driving simulators. This experimental setup is therefore considered as the standard and the methodology is only mentioned if the data were not collected using a driving simulator. If several articles were published based on the same data, the results are only considered once. In such a situation, and when available, the peer-reviewed journal article was used as reference.

In terms of issues investigated, the experimental results analysed across the experimental articles of the corpus have been regrouped in four categories. The data relative to human supervision under regular HAD are presented at first (3.2). Then, situations requiring the driver to regain control in case of an emergency or not as well as the contextual and individual influence have been considered (3.3). Next, the focus was set on how drivers decide to leave control to automation if the choice to use it or not is offered (3.4). Finally, HAD after-effects on manual driving is presented (3.5).

3.2. Human supervision in normal highly automated driving conditions

In an early study, drivers were asked to follow a lead vehicle at a comfortable distance and attend to a secondary task whenever possible. With HAD, the participants drove closer to the centre of the lane and to the lead vehicle than they did in the case of manual control (Stanton and Young 1997). These results were interpreted as indicating an improvement in lane-keeping performances and a more consistent adjustment to the speed of the lead vehicle. The drivers were also found to perform better on the secondary task, suggesting that HAD freed up certain cognitive resources.

This could explain why drivers tend to engage more and more in non-driving tasks with automation increase. This trend has been reported in a variety of tasks, including the use of an in-vehicle DVD player, which was used 2.6% of the time in a manual driving situation, 4% with ACC and 32.5% with HAD; or an eating frequency multiplied by a factor of 3.9 between manual driving and HAD. In nine percent of the time, drivers even read a magazine when driving with HAD, a behaviour never observed in manual or partly automated driving (Carsten et al. 2012). These potentially hazardous behaviours have also been observed in real test-track driving, with two-thirds or more of drivers looking for something in a rear compartment or eating, and half texting or emailing during a drive lasting less than two hours (Llaneras, Salinger, and Green 2013). About a quarter even fell asleep (Omae et al. 2005).

Even if non-driving tasks are not available or selected, drivers tend to shift their visual attention away from the road, including from the key tangent point areas, when functions are delegated to an automation system (HAD: Carsten et al. 2012; AS: Mars and Navarro 2012). More specifically, there is (a) a progressive disengagement of visual attention and (b) a progressive engagement in non-driving tasks as we move from the delegation of longitudinal control, through the delegation of lateral control and on to HAD (Carsten et al. 2012). These differential effects due to automated lateral and longitudinal control confirm the different nature of these two types of control (e.g. Navarro et al. 2016). Indeed, in most situations, reducing speed increases increase drivers' safety margins (between the driven and a followed vehicle for instance), whereas any action on the steering wheel simultaneously decreases and increases drivers' safety margins (moving away from an obstacle or a lane boundary puts the vehicle at risk by directing it toward another obstacle or the other lane boundary). Additionally, HAD has been reported to increase the amount of time drivers spend with their eyes closed (Jamson et al. 2013) and their eye-blink rates (Cha 2003; Dambock et al. 2013). However, it should be noted that drivers' performances in terms of the number and speed of visual detections (with targets such as large barrels, trash cans or silhouettes) have been found to improve slightly with HAD compared to manual driving (Davis et al. 2008; McDowell et al. 2008).

The quality of HMC is impacted by the presence and quality of the feedback from the automation system. After presenting the same form of automation (ACC) to drivers in different ways, it was observed that automation that provides information to the driver is judged more trustworthy and acceptable than automation that does not provide information. Additionally, automation that shares the user's driving objectives is also found to be more trustworthy and acceptable than automation that does not (Verberne, Ham, and Midden 2012). These results may be related to the Common Frame Of Reference (COFOR) concept, 'COFOR is at the core of cooperation and plays a role similar to that of the current representation of the situation at the individual level in dynamic situation management' (Hoc 2001, 520). To cooperate efficiently, human and automation system must share information in order to establish not only a common representation of the environment but also 'representations of one's own or others' plans, intentions, goals, resources, risks, etc.' (Hoc 2001, 521).

A high level of driving automation is not necessarily continuous and can be implemented temporarily and for short periods under specific circumstances. Consequently, Partially Autonomous Driver Assistance Systems (PADAS) can take over from the driver to perform emergency braking or to steer away from an obstacle. PADAS have been found to be effective in reducing the number of accidents through the use of both emergency braking (Muhrer, Reinprecht, and Vollrath 2012) and AS for collision avoidance (Heesen et al. 2015; Schieben et al. 2014). However, AS for collision avoidance has been found difficult to handle when the system implements false avoidance manoeuvres (Kelsch et al. 2015; Schieben et al. 2014).

3.3. Regaining control from automation

This section summarises the main results collected when drivers are required to regain control from automation. The resumption of manual control may be associated with a degree of urgency that varies depending on the situation. We first consider emergency situations in which drivers have to react extremely quickly. We then look at situations in which drivers have more time to react. Finally, the known influences of the context and individual differences are presented.

3.3.1. Emergency situations

The resumption of manual control in emergency situations is a major concern. In a HAD condition in which the drivers were in a platoon of cars and had to take over speed control in an emergency situation in which automation failed, only half did so (de Waard and van der Hulst 1999). The ability to take over lateral control of the vehicle was also found to be impaired for a 20-s period after an automation failure causing the vehicle to drift toward the side of the road (Desmond, Hancock, and Monette 1998). Drivers' responses to an emergency braking by a lead vehicle in a car-following task have also been investigated. With HAD, the number of rear collisions was four times higher than with manual driving (Stanton et al. 2001). These results have been confirmed on numerous occasions in a variety of methodological setups and are associated with delayed braking and steering responses and an increase in the likelihood of collision (e.g. Dambock et al. 2013; Larsson, Kircher, and Andersson Hultgren 2014; Merat and Jamson 2009; Saxby et al. 2013). Other examples have been collected while driving with AS on a test-track in an experiment requiring drivers to regain manual control due to an obstacle in their path. The drivers' steering wheel responses were more expansive and their skirting times longer than in manual driving (Hoc et al. 2006). Similarly, later initiation of skirting manoeuvers, greater steering wheel amplitudes and acceleration, together with greater sideways movement into the opposite lane were observed when drivers had to override AS due to an obstacle located in their path (Navarro, François, and Mars 2016). Furthermore and in line with the description of HMCI presented in the introduction (Figure 3), HAD has been found to deteriorate driving performances more than ACC in the case of an automation failure (Strand, Nilsson Karlsson, and Nilsson 2014). The automation failure severity also tends to impact on driving performances. The more severe the automation failure, the more impaired driving performances are (Nilsson et al. 2013; Strand, Nilsson Karlsson, and Nilsson 2014).

3.3.2. Take-over request

Although a take-over request (TOR) cannot necessarily be fully planned, the changeover from HAD to manual driving in this case is not the consequence of a hazardous or urgent event. A TOR can be issued due to lane endings, lane closures or temporary lanes at the start of road works, for instance. Drivers' ability to resume manual control from HAD depends on the way the take-over is initiated. Two distinct take-over initiation conditions were compared (Merat et al. 2014). In one condition, drivers were required to regain manual control every 6 minutes (i.e. automation-initiated take-over). In the other condition, the return to manual control was based on the length of time the drivers spent looking away from the road ahead (i.e. drivers' visual behaviour-initiated take-over). Better steering performances were obtained when the return to manual control took place after a fixed duration than after an overly long period of non-attention to the road ahead. After a return from HAD to manual control due to the drivers' visual behaviours, their visual exploration of the environment remained erratic for up to 40 s after they regained control. This indicates that basing the decision to return control from HAD to the driver based on his or her visual disengagement from the driving task does not guarantee better performances.

The sensory modality used to convey the TOR is important. In HAD conditions, visual and auditory TOR have been found to be more effective than exclusively visual TOR for distracted drivers (Naujoks, Mai, and Neukum 2014). The difference between visual and auditory TOR, on the one hand, and exclusively visual TOR, on the other, has been found to be greatest for the most difficult take-over scenarios in which the TOR was issued in a bend for no obvious reason rather than at the end of the lane or at the start of a section of temporary lanes. Drivers also take longer to put their hands back on the steering wheel, depart farther from the centre of the lane and drive more unevenly with exclusively visual TOR (Naujoks et al. 2014). A haptic seat that provides spatial information about surrounding vehicles was found to accelerate the return to manual control in scenarios requiring lane changing and to improve driving performance and drivers' visual explorations immediately following the take-over (Telpaz et al. 2015). More generally, a survey of the literature reveals that vibrotactile feedback is extremely effective in refocusing drivers' attention on driving when used for the TOR (Petermeijer, de Winter, and Bengler 2016). What is more, the nature of the most suitable TOR seems to be context-dependent, with a vocal message (i.e. visual plus acoustic and vocal information) being more effective than an acoustic message (i.e. visual information plus a meaningless warning 'beep') at the end of a lane when HAD is no longer possible. By contrast, the reverse has been observed when the infrastructure is unavailable (Toffetti et al. 2009). People also tend to prefer multimodal TORs for urgent situations but would favour auditory messages for less urgent TORs (Bazilinskyy and de Winter 2015).

3.3.3. The influence of context and individual differences

The driving context has been shown to influence take-over time and quality depending on the traffic situation. In dense traffic, there are more objects to perceive and process and this therefore leads to delays in manoeuver initiation (Gold et al. 2016; Radlmayr et al.

2014). This critically impairs drivers' behaviours, with take-over times being longer and the quality of the take-over being impaired in the case of evasive manoeuvres (Gold et al. 2016). HAD has been found to be detrimental when drivers perform secondary tasks (Merat et al. 2012). The specific nature of the non-driving task drivers perform in HAD conditions (see Section 3.2) may impact on the speed and quality of take-over. On the one hand, cognitively demanding tasks hinder take-over in cognitively demanding take-over situations, but only do so to a lesser extent in easy and well-known take-over situations. On the other hand, motoric non-driving tasks are the most detrimental in the easy and well-known take-over situations (Gold, Berisha, and Bengler 2015; Radlmayr et al. 2014). The negative impact of engaging in non-driving tasks is also most clearly seen in demanding and time-critical situations rather than in easier and more familiar situations (Gold, Berisha, et al. 2015; Gold et al. 2013).

Not all drivers adopt the same behaviours when confronted with HAD. A model based on an analysis of individual gaze behaviours was constructed to determine the take-over time after automated driving. In this model, gaze behaviours are used to estimate drivers' attentional shift away from the road (see Section 3.2) and the related automation monitoring strategy (Zeeb, Buchner, and Schrauf 2015). This makes it possible to classify drivers along three categories based on their gaze behaviours in an HAD condition. This classification is, in turn, a good predictor of braking reaction times in the case of a changeover to manual control. Furthermore, driver's age (manipulated for two groups: under 28 or over 60 years old) was not found to significantly impact performances in take-over situations. However, older drivers were found to control their vehicle differently by maintaining a higher time to collision and braking more often and harder than younger drivers (Körber et al. 2016).

3.4. Leave control to automation

In a study in which drivers were offered an optional FAD for periods of 5 min during a monotonous drive, less than half used FAD once or more. Furthermore, those drivers who decided to use FAD did so only for about a third of the drive duration (Neubauer et al. 2012). These data are consistent with the reported relatively poor acceptance of HAD (see Section 4.5), indicate that most drivers do not currently expect more autonomy from their vehicles. Nevertheless, this does not indicate that people would not use highly automated vehicles if they were available, as suggested elegantly by Henry Ford's famous quote: 'If I had asked people what they wanted, they would have said faster horses' (cited in Chandler and Van Slee 2013). What is more, another study found that drivers used HAD about 80% of the time when automation was available by pressing a button on the steering wheel. It should be noted that the road type had an influence on automation use, being employed at the lower rate of 55% of the time on urban roads (Martens, Wilschut, and Pauwelussen 2008). Indeed, the decision to use automation is probably influenced by the specific characteristics of each combination of automation system and driver.

3.5. After-effects of highly automated driving

After driving for 30 min with FAD available to them at their own discretion, drivers were required to drive manually and were confronted with a van pulling out in front of them.

The steering reaction times of these drivers were longer than those of drivers who had no access to FAD prior to manual driving. In addition, drivers who have previously been offered FAD tend to exhibit poorer lateral vehicle control (Neubauer et al. 2012). Driving after automated driving (platooning) involving no particular events (e.g. emergency braking or obstacle avoidance) has also been found to be different from manual driving prior to automated driving. Time headway (during a car-following task) was reduced and the standard deviation for the lane position increased (Eick and Debus 2005; Skottke et al. 2014; Wille, Röwenstrunk, and Debus 2005). More specifically, after a 33-min drive with HAD and a very short time headway (0.3 s), the subsequent 10 km of manual driving were performed with a reduced time headway compared to pre-HAD manual driving (Skottke et al. 2014). In line with these results, the time headway used during platooning (longitudinal control automated but lateral control left up to the drivers) has an impact on subsequent manual driving. Shorter average and minimum time headways were measured after a short 0.3-s time headway than after a large 1.4-s time headway (Gouy et al. 2014). In sum, the 'driving style' adopted by automation influences drivers' subsequent manual driving.

4. Cognitive dimensions addressed

The purpose of this section is to focus on the cognitive dimensions and constructs used by researchers to explain drivers' behavioural changes associated to automation presented in the previous section (3 Issues investigated). Five categories of cognitive dimensions and constructs have been identified: attention, distraction and fatigue (Section 4.1), workload and situation awareness (Section 4.2), BAs and out-of-the-loop (OOTL) (Section 4.3), trust (Section 4.4) and acceptance (Section 4.5).

4.1. Attention, distraction and fatigue

Manual car driving primarily involves visual perception. It is therefore important to measure potential changes in terms of visual attention while driving a highly-automated vehicle. A disengagement of attention from an area known to be closely linked to vehicle steering during bend-taking (i.e. tangent point area, Land and Lee 1994; Lappi 2014) has been observed with AS (Mars and Navarro 2012; Navarro, François, and Mars 2016). This attentional shift away from relevant visual information when using automated driving has been confirmed in the case of motorway driving, in which a similar disengagement of visual attention from the road has been observed with both AS and HAD (Carsten et al. 2012). Equally, a test-track study has found a reduction in the amount of time spent looking away from the forward roadway (Llaneras et al. 2013). This attentional shift can translate into an equivalent improvement in performance in a visuo-spatial secondary task under AS and HAD conditions compared to manual driving (Stanton et al. 2001). When no secondary task was imposed, drivers were found to immerse themselves more in non-driving tasks with AS, and even more so with HAD, than when driving manually (Carsten et al. 2012). This attentional shift was not observed with devices that produce infrequent and brief actions, referred as PADAS. For instance, an autonomous braking system intended to prevent forward collisions did not lead to a greater visual involvement in secondary tasks (Muhrer et al. 2012).

HAD has also been found to induce passive fatigue, which translates into low task engagement and situations that pose few challenges for drivers (Saxby et al. 2013). To counter the negative effects of HAD in terms of fatigue and stress, drivers were able to choose to use full automation at their discretion for periods of 5 min during a 30-min drive. The subjective ratings of stress and fatigue states did not improve compared to manual driving (Neubauer et al. 2012). These new results confirm the idea that HAD 'may just be as effective in inducing fatigue and stress as prolonged driving under monotonous driving conditions' (Desmond et al. 1998, p. 12). Motivating secondary tasks have the potential to reduce drivers' drowsiness and such tasks could therefore be used to maintain a high level of driver alertness in HAD (Schömig et al. 2015).

4.2. Workload and situation awareness

Closely linked to attention (Wickens 2002; Wickens and Hollands 2000), workload is one of the major concepts used in ergonomics (Young et al. 2015; Young and Stanton 2004). Studies conducted in the late 90s reported a decrease in drivers' workload with HAD compared to manual driving. When driving was performed automatically, drivers' activation levels, mental effort, and subjective mental workload were reduced, whereas performances in a secondary task improved (de Waard and van der Hulst 1999; Desmond et al. 1998; Stanton and Young 1997). A recent meta-analysis of both workload and situation awareness based on empirical evidence collected during the use of ACC and/or HAD provides a great deal of information on these cognitive constructs (de Winter et al. 2014). In line with the attentional effects reported in the previous Section (4.1), this meta-analysis revealed an average decrease in subjective mental workload as assessed through questionnaires, namely from 43.5% in manual driving to 22.7% with HAD (de Winter et al. 2014). This meta-analysis also revealed an average increase of 161% in the number of tasks completed on an in-vehicle display in the HAD compared to the manual driving condition (see for instance Flemisch et al. 2008). The above-mentioned decline in driving performances when it is necessary to take over manual control from HAD may be related to driver underload (Young and Stanton 2002). However, the fact that impaired performances have also been observed without workload reduction (Desmond et al. 1998) supports the idea that other psychological phenomena may also be responsible for the difficulties observed when drivers resume manual control.

The loss of situation awareness (Endsley 1995) with HAD is also considered to be an important cognitive explanation for the difficulties experienced when resuming manual control. Compared to manual driving, HAD can improve situation awareness if drivers are asked to find objects in the environment but can also impair situation awareness if drivers engage in non-driving tasks (de Winter et al. 2014). In most cases, situation awareness has been found to be greater in drivers who manually steer their vehicles than in drivers who supervise HAD automation (e.g. Jamson et al. 2013; Merat et al. 2012). This suggests that in natural conditions, drivers tend to engage in non-driving tasks and consequently experience a loss of situation awareness.

4.3. Behavioural adaptations and out-of-the-loop phenomenon

The most critical negative BA associated with HAD is related to emergency situations requiring manual interventions. For instance, in a condition in which the lead vehicle performed an emergency braking manoeuvre, the number of rear-end collisions with HAD was four times higher than with manual driving (Stanton et al. 2001). HAD has also been found to have negative after-effects on manual driving that persist for several kilometres after automation has been deactivated (Gouy et al. 2014; Skottke et al. 2014). These HAD after-effects have been observed for both longitudinal (i.e. time headway reduction corresponding to a reduction in safety margins) and lateral control (i.e. increased standard deviation of lateral position corresponding to laxer control). Consequently, BAs are not restricted to automation use itself but can also be expected after the use of HAD. Interestingly, even temporary automation mechanisms, as in vehicles equipped with a forward collision warning and autonomous braking system (PADAS), have been found to trigger negative BAs in the form of higher driving speeds (Muhrer et al. 2012). This indicates that even non-continuous vehicle control interventions by the automation system impact on global driving behaviours.

The OOTL phenomenon is due to the change in the drivers' activity: from operating to supervising driving. It has been observed that asking drivers to resume manual control when they shift their visual attention away from the road ahead for too long is not a good way of keeping them in the driving loop (Merat et al. 2014). Indeed, if a changeover from HAD to manual control is required when drivers are considered to be visually OOTL, subsequent steering and visual performances are degraded. The OOTL phenomenon is also used to explain drivers' increased response times (Larsson, Kircher, and Andersson Hultgren 2014), minimum time headway reduction and the increase in the number of situations that reach the point-of-non-return in the event of automation failure (Strand et al. 2014). These results tend to indicate that drivers should be kept in the control loop rather than being asked to re-engage in the loop on an occasional basis. In practice, countdowns have been found to be a promising way of preparing drivers and therefore improving changeovers between automated and manual driving (Larsson 2016). Another way of preventing OOTL is to keep drivers responsible for certain control activities, as implemented in the form of haptic shared control automation devices (e.g. Abbink and Mulder 2009; Abbink, Mulder, and Boer 2012; Mulder, Abbink, and Boer 2012).

4.4. Trust

Trust is a key cognitive dimension associated with automation in a variety of application areas (see for instance Lee and See 2004; Muir 1994). Trust has been shown to be linked to drivers' gaze behaviours during HAD. The higher the level of drivers' declared trust in automation, the less frequently they monitor it (Hergeth et al. 2016). This is consistent with the 'inverse relationship between trust and the monitoring of automation' reported earlier (Muir and Moray 1996). Trust in HAD automation has also been found to increase progressively during automation use, despite being temporarily reduced by TORs (Gold et al. 2015; Hergeth et al. 2015). Furthermore, a positive correlation exists between drivers' trust in FAD and take-over speed, with drivers' response times increasing in proportion with their level of trust (Payre, Cestac, and Delhomme 2016). The relationship between trust and take-over speed changes over time and become insignificant for drivers with a high level of FAD practice (Payre, Cestac, and Delhomme 2016). The fact that the association between trust in a highly automated vehicle and driving behaviours has not been systematically observed probably means that the link is a subtle one (e.g. Kircher, Larsson, and Hultgren 2014). Indeed, trust in HAD may be mediated by individual variables. While drivers' gender does not seem to have any great impact on trust and acceptance (Wintersberger and Riener 2016), young drivers have been found to be more inclined to trust automation than middle-aged and older drivers (Wintersberger et al. 2016) or, conversely, to rate automation less positively than older drivers (Gold, Körber, et al. 2015). The inconsistent results regarding (a) the relationship between trust in HAD and driving behaviours and (b) the influence of drivers' age might be due to several interfering factors such as social dimensions and automation feedback.

Indeed, social cues can improve trust in HAD (Zihsler et al. 2016). Furthermore, trust in automation is known to be influenced by the feedback provided to drivers. Feedback is a widely used term and concept in the field of psychology that refers to information that emerges from the environment in order to be used by humans. Here, only driving automation-induced feedback is considered (Stanton and Young 1998, 2000). Feedbacks has been found to have a causal link with attention, mental workload and situation awareness (Heikoop et al. 2015). For instance, ACC systems that share the driving goals or provide information to drivers are judged more trustworthy than those that do not (Verberne, Ham, and Midden 2012).

4.5. Acceptance

Trust is also known to influence acceptance of automation (e.g. Miglani, Diels, and Terken 2016) in such a way that ACC systems that share the driving goals or provide information to drivers are also judged more acceptable than those that do not (Verberne, Ham, and Midden 2012). Most of the studies conducted on the acceptability of driving automation have focused on the lower LOA and associated HMC modes rather than HAD (Özkan, Lajunen, and Kaistinen 2005). The few studies available indicate that drivers are not necessarily enthusiastic about the introduction of HAD. Indeed, more than three quarters of drivers declared that they would not want to use HAD if they were required to supervise automation (Omae et al. 2005). Confirming earlier results, only 34% of the participants in a HAD simulation experiment stated that they wished to have this automation in their own vehicle (Bekiaris, Petica, and Brookhuis 1997). The poor acceptance of HAD is most likely due to the need to supervise the automation system. Indeed, drivers are largely favourable to FAD automation, with 68.1% out of 421 participants scoring above the median value on an FAD acceptability scale. FAD was also generally judged to be beneficial for impaired driving and of greatest use on highways, in congested traffic and for automatic parking (Payre, Cestac, and Delhomme 2014). Even if HAD and FAD are very similar in terms of technology, opposite patterns of results are reported for drivers' acceptance. HAD is rejected by most drivers whereas FAD is mostly accepted. These results correspond to the description of HAD as an HMC mode with weak HMCI (see Figure 3) that leaves drivers mainly responsible for driving but with restricted authority, control and ability (see Table 2). This explains the massive rejection of HAD by drivers and encourages solutions that more fully transfer the four cornerstone concepts of HMC from drivers to automation.

5. Current and future issues and challenges

The current literature review contains a summary of the empirical works that have focused on HAD. The studies conducted to date have provided a number of insights into human in-vehicle behaviour in a variety of situations, including when HAD works smoothly, in cases when the resumption of manual control is required or possible, and also with regard to manual driving following HAD. The implications of HAD use for several human cognitive dimensions have also been highlighted. Based on the main outcomes of this previous research, a number of future research directions are proposed below.

Generally speaking and as observed in a number of experiments using various methodologies, HAD reduces mental workload (de Winter et al. 2014). This means that drivers can make use of the cognitive resources previously devoted to driving for other tasks. The relevance of these non-driving tasks depends on the context. From the driver's perspective, watching a DVD could be the most relevant task (e.g. Carsten et al. 2012). However, in a military context, detecting targets or silhouettes could also be relevant and might be improved by HAD (Davis et al. 2008; McDowell et al. 2008). When task relevance was manipulated experimentally by instructing drivers to perform visual secondary tasks located away from the road, a drop (from 77% to 63%) in the rate of detection of objects that appeared suddenly at the side of the road was observed with HAD compared to manual driving (Barnard and Lai 2010).

Overall, drivers appear to disengage from the driving activity not only cognitively but also in terms of sensory-motor coordination and this involves a disengagement from visually relevant information (Carsten et al. 2012; Mars and Navarro 2012; Navarro, François, and Mars 2016). Two options can therefore be considered: first, drivers should not be expected to supervise automation (Farber 1999), or, second, if drivers are required to keep on supervising HAD for extended periods of time (Merat and Lee 2012; Nilsson 2005), appropriate countermeasures should be designed. HAD technology does not yet possess the perfect level of reliability enabling it to replace drivers. If HAD is implemented in its current condition then drivers' disengagement must be compensated, in order to improve the changeover from automated to manual control.

A first option would be to adopt another automation philosophy such as that proposed by Flemisch with the H-metaphor (Flemisch et al. 2003, 2008; Flemisch, Bengler, Bubb, Winner, and Bruder 2014; Kienle, Damböck, Kelsch, Flemisch, and Bengler 2009). In line with this philosophy, a form of haptic shared control in which both the automation system and the driver act on the steering wheel at the same time has been designed (e.g. Steele and Gillespie 2001). When compared to manual driving and AS, haptic shared steering control was found to reduce the need for human control on the steering wheel and improve safety performance while keeping the driver in the control loop (Mulder, Abbink, and Boer 2012). This automation philosophy offers the most intense level of HMC as illustrated in Figure 3 and has repeatedly been proven to be effective (Abbink and Mulder 2009; Abbink et al. 2012; Abbink, Mulder, Van der Helm, and Boer 2011; Melman, de Winter, and Abbink 2017). The actuators currently used to control the vehicle could even be redefined to fully exploit the potential of the H-mode, for example by using a steering wheel whose orientation is hidden to the driver (Kerschbaum, Lorenz, and Bengler 2014). This could even result in a bidirectional haptic interface to replace the traditional steering wheel and pedal actuators (Kienle, Damböck, Bubb, and Bengler 2013).

A second option would consist in keeping drivers actively engaged in the control loop by using exclusively driver-initiated automation (Banks and Stanton 2016a, 2016b). This approach, representing a compromise between only partially reliable HAD use and drivers' cognitive mechanisms at work with HAD, appears promising. Drivers remain in charge of decision-making but decide to delegate longitudinal and lateral control to automation. This driver-centred vehicle automation approach (Banks and Stanton 2016a, 2016b) shares theoretical similarities with the H-metaphor (Flemisch et al. 2003, 2014), as drivers remain in charge of the strategic decisions but are not engaged at an operational level (according to the terminology proposed by Michon 1979, 1985). While riding a horse, the rider decides the direction in which the horse should go but delegates the operational tasks associated with the movements (e.g. the horse's gait) to the animal. While driving an HAD vehicle, drivers would decide what function should be delegated and when. In both cases, the human can decide to stop using the animal or the automation, and walk or drive manually. In this way, the human retains the responsibility and general authority for driving, but decides whether or not to delegate control of a variety of driving sub-tasks, thus also retaining driving ability. Further research is required to investigate in more detail how this can be achieved in practice, especially if the driving tasks are delegated to automation for extended periods of time.

A third option is already used with PADAS. Automation only intervenes under specific circumstances and only for a brief period. This type of automation has been shown to be effective in improving performances and does not continuously modify drivers' activity because the intervention is restricted to certain driving situations (e.g. obstacle avoidance or emergency braking). This option is the opposite of the previous one along the authority dimension since authority lies with the automation system. Because automation only takes control temporarily and under specific circumstances, drivers retain overall responsibility, ability and control. It is worthy of note that the non-continuous nature of interventions by the automation system does not guarantee perfect HMC. For instance, as described above, negative BAs have been observed with PADAS (Muhrer et al. 2012).

A fourth solution could be to identify the task(s) which the human behind the wheel performs and to adapt the interventions on the part of the automation system accordingly. To our knowledge, highly automated vehicles have so far only considered information in the environment outside the vehicle, but have gathered no information on what occurs inside the vehicle where the driver sits! This approach implements automation without considering the driver. However, drivers' attention, behaviours, workload… could be taken into account by an automation solution. In our opinion, the main future challenge for automation from both the ergonomic and technological perspectives is not to create a fully automated vehicle (i.e. autonomous car) or to handle the changeover between automated and manual driving. Instead, research efforts should focus on the adaptation of automation interventions in the light not only of the driving environment but also of the driver's past and current behaviours, abilities and internal state. This is a huge challenge given that humans are complex multi-dimensional animals who use a specific form of largely unpredictable logic: psycho-logic. Some researchers have already attempted to embark on this path by capturing and modelling the internal states of drivers inside the vehicle in order to adapt TORs accordingly (Goncalves, Olaverri-Monreal, and Bengler 2015). Other researchers have also analysed eye-movement parameters in order to determine the driver's current task (Braunagel et al. 2015).

It is not only necessary for automation to pay more attention to drivers. At the same time, attention should be paid to the construction and updating of the common frame of reference shared by drivers and highly automated vehicles. To this end, automation should share information with drivers in an easily comprehensible way in order to facilitate HMC. Appropriate solutions must be conceived of and developed. The use of analogue head-up displays to provide visual feedback from the automation actions has been found to improve drivers' reaction to automation failure, for instance (Damböck et al. 2012). This approach could be extended to time headway, speed, traffic… in order to keep drivers in the control loop. Automation and the associated feedbacks could also be adapted to each individual driving style to individualise HMC and enhance convenience of use (Bellem et al. 2016; Scherer et al. 2015).

Another research direction that should be investigated relates to the influence of automation over longer periods of time. Most HAD experiments have been conducted during a very restricted time period (typically less than two hours). It has been shown that prior experience of ACC improves drivers' performances in the event of an automation failure compared to drivers who have never previously driven with ACC (Larsson, Kircher, and Andersson Hultgren 2014). A trend also reported for the speed and quality of take-over between the beginning and end of one and the same experiment lasting approximately only 80 min (Körber et al. 2016). The difficulties drivers experience on HAD failures and when having to resume manual control are also probably due to their lack of experience with HAD.

Figure 4 illustrates how automation failure impairs driving performances in the light of the mode and intensity of HMC. Just because HMCI is low, this does not mean that

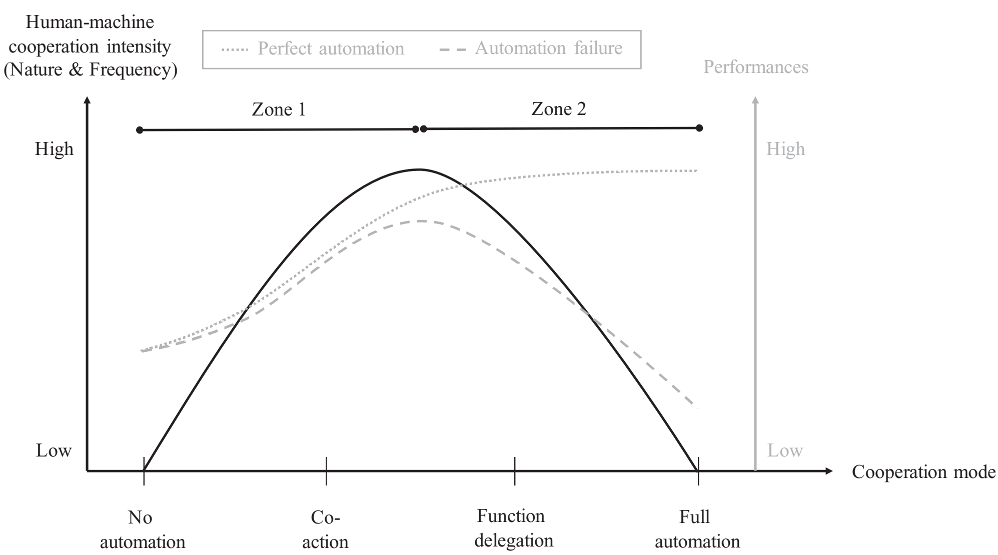

Figure 4. The inverted U-shaped curve describes the intensity of human–machine cooperation together with the cooperation modes. The grey curves represent driving performances from low to high depending on the cooperation modes and the intensity of human–machine cooperation either with perfect automation (dotted line) or in the case of automation failure (dashed line). Two zones are defined to distinguish between relatively similar performances (zone 1) or massive differences (zone 2) between perfect automation and automation failure.

driving performances will fall only slightly in the event of an automation failure. Instead, HMCI is thought to interact with cooperation modes to explain driving performances. In zone 1, perfectly reliable automation improves driving performances but is not highly detrimental in the case of automation failure (see Navarro 2017 for a review). By contrast, in zone 2, perfectly reliable automation improves driving performances more than in zone 1 but is accompanied by a massive decline in driving performances in the event of automation failure. In zone 1, the higher the HMCI is, the better the driving performances are with both perfect automation and imperfect automation. In zone 2, the higher the HMCI is, the larger the gap between driving performances with perfect automation and imperfect automation. In other words, the impact of automation failure is more detrimental in zone 2 than in zone 1 and is inversely proportional to the HMCI in zone 2 only. A general recommendation would therefore be to avoid automation failure in zone 2 or, alternatively, to implement automation in zone 1.

6. Conclusion

Irrespective of what anyone may feel about the topic, highly automated vehicles are set to bring about profound changes in mobility. Highly automated vehicles form part of the category of automation that replaces humans in a variety of tasks which they used to perform without automation and involves a number of issues including the general usefulness of automation. People are known to prefer to perform repetitive and monotonous tasks manually rather than to use full automation, even if it is twice as fast (Navarro and Osiurak 2015; Osiurak et al. 2013). When they have nothing to do, most people in one study were even observed to give themselves electric shocks rather than experience boredom (Wilson et al. 2014). This general psychological trend has been confirmed in the case of HAD with drivers performing non-driving tasks because the task was judged boring and they wanted something to do (Omae et al. 2005).

Historically, humans have always attempted to develop and use smarter and more effective tools (automation is one type of current smart and effective tool) to make life easier. However, when those tools are so developed that they become more efficient than us in ensuring the successful completion of a task, we worry about the fact that they are replacing us! This may be because the issue of tool use has not been correctly addressed. Human culture and tool use are not separate from one another. Tools shape humans as much as humans shape tools. Indeed, humans and tools have a symbiotic relationship (Hancock and Hancock 2013). Tools are the direct extension of human intelligence, just as echolocation is the direct extension of bats' intelligence. More precisely, human tools cannot be distinguished from human intelligence since tool use is a characteristic of humankind. Similarly, echolocation is a characteristic of bats' intelligence, allowing them to catch flies in a completely dark room, for instance (see de Waal 2016 for more details on animal intelligence). We humans simply tend to be misled by the fact that our tools are extraneous to our bodies. Tools, however, are a direct manifestation of our intelligence.

The new irony of automation, even deeper than the one initially described by Bainbridge (1983), is that the fruit of our intelligence is leading to the design of tools that are capable of completing tasks without us and doing so more effectively than we are able to. The tools humans use are a simple expression of their intelligence and can therefore be considered as a direct physical and cognitive extension of them. How then can tools exceed our understanding? This is probably the result of cumulative collective intelligence that exceeds individual intelligence, even for individuals of exceptional intelligence (Enquist et al. 2008). It is referred to as the ratchet effect, i.e. the cumulative knowledge elaborated by a group of people and transmitted from generation to generation, makes it difficult and unintuitive at an individual level to realise that automation is simply part of humanity. Tools therefore go beyond our individual intelligence even though they are a result of that same individual intelligence. Tools, and more particularly high level automation, therefore exceed individual human intelligence: that is the new irony of automation.

This explains why automation appears to be something external and is sometimes perceived as destroying human professional activities. In the same way that road cleaning machines replaced human road sweepers and industrial machines replaced manual operators, autonomous vehicles may in the future replace truck drivers, cab drivers or delivery drivers. By replacing humans in their daily activities, automation is transforming humans in a more general way since humans need to be kept busy and do other activities. To conclude, HAD raises specific questions concerning driving, particularly in terms of safety, but also much more general questions regarding the nature of our relationship with tools.

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