Transition of control in highly automated vehicles

A literature review

SWOV
INSTITUTE FOR
ROAD SAFETY RESEARCH

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Report documentation

Executive summary

The Directorate-General of Highways, Waterways, and Water Systems (Rijkswaterstaat in Dutch) of the Ministry of Infrastructure and the Environment (Ministerie van Infrastructuur en Milieu (IenM) in Dutch) has commissioned SWOV to conduct a literature review about transition of control in highly and fully automated vehicles from the perspective of the driver. Transition of control is the switch from fully automated driving to manual driving while in traffic. If the system of fully automated driving happens to fail or makes a mistake, or if drivers want to drive their vehicle manually, drivers have to switch from being driven to manual driving. This report presents the current knowledge about human behaviour in highly and fully automated vehicles and the psychological processes that influence task execution before, during and immediately after transition of control. The report also contains suggestions for further research and recommendations for policymakers.

The future development of fully automated vehicles cannot yet be fully predicted. Most probably an increasing number of fully and partly automated vehicles will enter into our roads and have to mix with other road users, including pedestrians and cyclists. Vehicles will not all be at once the fully automated vehicles in the way the Google car has been designed. There will be a mixture of vehicles with different levels of automation and this will gradually change into a mixture of vehicles with higher levels of automation becoming dominant. Only in the level-5 automated vehicles (see for a description *Figure 1.1*) that automatically drive their occupants to their destination, transition of control will not be necessary. This can only occur under the condition that these vehicles can master all possible traffic situations and weather conditions and that the automated systems in these vehicles will never fail. In all other situations transition of control is inevitable.

It is widely assumed that automation of the driving task will be beneficial for road safety, because automated systems do not speed, do not drive under the influence of psychoactive substances, never get tired, et cetera. On the other hand, automated vehicles may also have negative effects on road safety. For instance, crashes may happen when drivers have to switch to manual driving while they are not mentally ready to do this. Negative effects will most probably also occur when other road users have to anticipate fully automated vehicles not behaving according to expectation. This literature study will only discusses the first problem and not with the interactions between other road users and automated vehicles.

There is a distinction between planned moments, when the driver has to switch to manual driving (e.g. when fully automated driving is only possible on motorways and the driver wants to leave the motorway) and acute moments, when the driver has to resume to manual driving (e.g. when the system fails or the system cannot manage the traffic situation).

The mental processes that take place and the way these processes can affect driver behaviour while driving in a highly automated vehicle and during transition of control can be studied from different theoretical perspectives or

paradigms. The dominant paradigm is the human factors paradigm. This paradigm focuses on human information processing. While driving in the fully automated mode, drivers will experience a loss of situation awareness, due to a low workload in which not much information related the driving task has to be processed. This diminished situation awareness will not be immediately reactivated after drivers have switched to manual driving. Indeed, a multitude of studies have indicated that diminished situation awareness occurs when task demands regarding the driving task are low, due to the automatization of the driving task. There are also some studies in which it was found that situation awareness was diminished in acute threatening situations, directly after resumption of the driving task. This is even more so the case when the transition of control occurs suddenly and the driver paid no attention to the driving task just before transition of control. Studies indicate that driving performance at the operational level (the longitudinal and lateral control over the vehicle) is also affected after transition of control.

Another paradigm is the motivational one: do drivers trust the automatic systems and what is the effect of trust on drivers in highly automated vehicles? This paradigm predicts that drivers will tend to rely too much on the flawlessness of the automated systems. When too much trust is placed in automation, a false sense of security will arise, which results in a loss of risk-awareness. The effects of trust and other psychological factors on the quality of transition of control have not been studied yet.

Again, another paradigm is dual processing. Dual process theories make a distinction between routine actions and conscious actions. While driving in the fully automated mode, the brain structures (schemata) that allow for routine actions will no longer be activated. These schemata create mental representations that help drivers to recognize the traffic situation, to predict what may happen and to act quickly. Dual process theories predict that after resumption of control over the vehicle, only slow and error-prone conscious actions can be executed before 'normal' driving takes over. This may result in poor hazard anticipation skills and behavioural habituation. For instance, it was found in one study that drivers kept driving too closely to a lead vehicle too long after the platoon of automated vehicles was lifted.

We have identified the following subjects for further research:
– Duration of diminished situation awareness regarding acute threats, in particularly regarding latent hazards;
– The influence of the driver state on the duration of the diminished situation awareness;
– The optimum interface to turn drivers who are out-of-the-loop back in-to-the-loop, and
– The influence of trust in the system on the severity and duration of loss of situation awareness regarding latent hazards in real traffic.

Preliminary recommendations for vehicle authorities are:
– Allow only highly automated vehicles with fail-safe systems that function in all possible traffic situations and weather situations on roads where automated driving is possible. Only with these systems, abrupt transitions of control can be avoided;
– Allow only interfaces of systems that effectively get drivers in-to-the-loop just before transition of control in planned transitions.

A preliminary recommendation for road authorities is:

- When there are permanent sections on the road (e.g. when automated driving is possible on motorways and drivers have to switch to manual driving as soon as they leave the motorway) where drivers have to switch from automated driving to manual driving, circumstances should be created to avoid hazards from occurring. For instance, no other vehicles should be in the vicinity so as to avoid collisions with automated vehicles due to transition of control errors.

A preliminary recommendation for driving licence authorities is:

- Facility training programs for learner drivers that teach them to drive in automated vehicles and that teach them to resume manual driving while in traffic.

Contents

1.   Introduction

1.1.   Potential safety benefits and other benefits of automated vehicles

Human errors and traffic violations are the underlying factors of many road accidents. These are crashes in which, for instance, hazardous speeding, inattention or distraction, misinterpretation of the developing traffic situation, or driving under the influence of psychoactive substances contribute to crashing. Sensors, combined with computer technology that can perform the driving tasks, ideally do not commit violations, do not make errors, are always attentive and do not get tired. There are already devices that outperform human drivers because they can detect objects and process information faster than humans. For instance, the full auto brake and pedestrian system that has been developed by Volvo[1] can detect pedestrians and cyclists on collision course and will perform an emergency brake when the driver does not respond to system alert. The fact that machines can detect and process information faster than humans - as is the case in full automated pedestrian brake systems - not only helps to improve road safety, but also allows for platooning. A platoon is a group of successive vehicles that drive with a very short headway. This increases road capacity and saves fuel. Finally, automated vehicles can be convenient for 'drivers' because, on one hand, they do not have to perform the sometimes tedious and boring driving task (i.e. they do not have to remain attentive while little is happening) and, on the other hand, they do not have to make fast decisions and execute tasks in complex traffic situations (i.e. situations with a high mental workload). Although fully automated vehicles can improve road safety, a first analysis of a few crashes involving fully automated vehicles on the open road has not indicated that the crash rate of fully automated cars is lower than the crash rate of conventional cars (Sivak & Schoettle, 2015).

1.2.   Transition of control

It is not expected that fail-safe fully automated vehicles that act correctly in all circumstances will replace all human controlled vehicles overnight. It is not yet clear how the introduction of automated vehicles will develop. Will it be the route of cooperative systems in which vehicles communicate with other vehicles and the infrastructure? Will it be the route of fully automated vehicles such as Google car? Or will it be a mixture of the two (Timmer & Kool, 2014)? The Society of Automotive Engineers (SAE) and the National Highway Traffic Safety Administration (NHTSA) have developed schemes about levels of automation that are quite similar. In *Figure 1.1* the SAE scheme is presented and in the last column of this scheme a comparison is made with the levels that NHTSA has developed .

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[1] See: http://phys.org/news/2011-02-volvo-pedestrian.html

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

Figure 1.1. *Levels of automation.*
Source: http://cyberlaw.stanford.edu/files/blogimages/LevelsofDrivingAutomation.pdf

A gradual development from level 0 to level 5 is one option, but some levels may also be skipped. Most probably, there will be a gradual development of various levels with vehicles with higher levels of automation becoming dominant. For instance, starting from level 2, when a vehicle has adaptive cruise control (ACC) that automatically controls longitudinal motion and also has a lane-keeping system that automatically controls the lateral position of the vehicle and both are switched on, a driver does not have to steer or control the pedals actively. Vehicle manufacturers such as BMW, General Motor, Mercedes and Volvo already produce vehicles that have both automated longitudinal and lateral control but the two are not interrelated yet[2]. Tesla also had separate automated longitudinal and lateral control systems, but due to a software update these two systems are now combined[3]. This means that a Tesla can drive automatically as long as no intentional lateral and longitudinal movements are required (e.g. when leaving the motorway or when overtaking another vehicle). Although a Tesla can drive automatically in certain circumstances, it is required that the driver keeps his hands on the wheel at all times.

In a vehicle approaching level 3, as is the Tesla, the driver will frequently-have to switch from being driven to manual driving. In more advanced level 3 vehicles there will be switches at spots where automated driving no longer is possible (e.g. when automated driving is only possible on motorways but not

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[2] See the websites: http://www.bmw.nl/nl/content/meer-bmw/bmw-connecteddrive/highly-automated-driving.html, http://www.extremetech.com/extreme/154555-are-we-there-yet-cadillacs-semi-self-driving-car-with-super-cruise, https://www.daimler.com/dccom/0-5-1210218-1-1210351-1-0-0-1210228-0-0-135-0-0-0-0-0-0-0.html, https://www.daimler.com/dccom/0-5-1210218-1-1210321-1-0-0-1210228-0-0-135-0-0-0-0-0-0-0.html, http://www.volvotrucks.com/trucks/uk-market/en-gb/trucks/volvo-fh-series/key-features/Pages/driver-support-systems.aspx.
[3] See the website: http://www.bbc.com/news/technology-34603364.

on secondary roads), when the system fails, or when the system cannot handle the traffic situations. There will be fewer switches to manual in level-4 vehicles, whereas there only will be switches to manual driving in level-5 vehicles when the system fails.

Resumption of manual control by the driver when vehicles no longer can drive in the fully automated mode is called transition of control (i.e. a switch of control from the automated vehicle to the driver). This transition can be abrupt when the system suddenly fails, compared to being planned, when, for instance, automated driving is only possible on motorways and the driver wants to leave the motorway. This report is about the behavioural aspects just before, during and directly after transition of control in abrupt transitions (e.g. when the system suddenly fails) as well as in planned transitions (e.g. at exits when the driver wants to leave the motorway and fully automated driving is only possible on motorways).

1.3. Literature search

For this literature review a comprehensive literature search was conducted using the following Boolean search string: ('automated' OR 'transition of control' OR 'transition to manual' OR 'autonomous' OR 'situation awareness' OR 'automation' OR 'workload') AND (driv* OR vehicle* OR car*). The databases included are the SWOV library, Google Scholar and the Elsevier SCOPUS .

1.4. Outline of the report

How drivers behave when they are a passenger in their own vehicle and how they behave when they switch from passenger to driver depends on many different aspects. For instance, does the driver trust the system? When drivers do not trust the system, they will remain vigilant and maybe hover with their hands just above the wheel while the vehicle is in the fully automated mode. They will constantly monitor the system and the traffic environment while they do not actively drive. For these drivers transition of control will be different from drivers that trust the system and can be asleep or engaged in tasks not related to the driving task (e.g. reading or watching a movie) when suddenly an alarm goes off that alerts them that they have to resume the driving task immediately. The human factors that influence transition of control will be discussed in *Chapter 2*. This is done on the basis of different psychological theories about driver behaviour. What do these theories predict about the driving performance directly after resumption of the driving task? Do they predict, for instance, that the ability to detect possible hazards is diminished in the first few seconds after resumption? In *Chapter 3* the few studies that especially have been conducted to study transition of control in highly automated vehicles will be discussed separately. In this chapter the needs for further human factor research will also be listed. *Chapter 4,* The last chapter of this literature review, summarizes the most important findings. Preliminary recommendations for policymakers are also mentioned in this chapter.

2.   Driving behaviour in highly automated vehicles

2.1.   **The effects of automation on driver behaviour**

This chapter is about the effects automation has on the mental states of drivers and their behaviour while driving in the fully automated mode. The effects of these changes in mental states and behaviour on transition of control will be discussed in the next chapter (*Chapter 3*). Automation has an effect on many factors, for instance: workload, situation awareness, confidence, locus of control, habitual adaptation and hazard anticipation. The dominant paradigm to study the effects automatization of the driving task has on drivers is the human factors paradigm. However, factors such as trust, locus of control and habitual adaptation are not covered by this paradigm. These factors will be discussed on the basis of the motivational paradigm and the dual processing paradigm. This chapter starts with some general effects that automation has on human beings having to supervise highly automated systems.

2.2.   **The ironies of automation**

More than three decades ago, Lissane Bainbridge was the first to point out that although automation is beneficial in many instances, including road safety, there are some aspects that could negatively influence these benefits (Bainbridge, 1983). Drawbacks occur when it is the task of the driver to supervise automated systems that normally function well without human intervention, but occasionally and sometimes unexpectedly require the driver to make decisions and to act in atypical conditions (e.g. when the system fails). These drawbacks she called the ironies of automation. One of these ironies is that the driver loses his practical skills because he rarely actively drives anymore. Automated systems tend to fail in difficult circumstances. So the driver has to use his diminished skills (due to a lack of experience) in mostly difficult circumstances. Another irony is that drivers have to monitor the system while nothing happens. In these circumstances it is difficult to remain vigilant and to notice abnormalities that require decision-making by the driver. Hancock (2013) wrote: "If you build a system where people are rarely required to respond, they will rarely respond when required."

According to Flemisch et al. (2012), there are four factors that define the relationship between drivers and highly automated vehicles where the automated systems primarily perform the driving task and the driver performs the driving task occasionally. These factors are: ability, authority, control and responsibility. The distribution of these factors between man and machine can differ in different situation. On the whole, machines have more abilities (react faster, do not get tired, et cetera) but man has mainly greater authority. This means that humans can always overrule the machine. However, the machine sometimes overrules humans. In the full auto brake and pedestrian system that is described in *Section 1.1*, the vehicle automatically brakes when the driver fails to brake. Automated vehicles can only do this when they not only can perform the driving task but also can monitor and control the driver. Therefore, in cooperative situations, the vehicle controls the driver and the driver controls the automated systems. When something goes wrong (e.g. there is a crash) someone is responsible.

A machine cannot be blamed, but the manufacturer of the automated system can be. In automated vehicles, drivers, manufacturers of automated vehicles, the companies that maintain the vehicle, the authorities that certify automated vehicles, and road authorities can all be held responsible.

2.3. Driving simulators

All the studies mentioned in this report about driving behaviour in highly automated vehicles are simulator studies. In some of these studies the researchers have made use of very advanced simulators in which drivers also experience the forces on their body when the simulator vehicle brakes, accelerates, or turns for instance. The driving simulator of the University of Leeds is such a high-end simulator that also simulates the feeling of driving and in which studies about transition of control have been conducted (see *Figure 2.1*).

Figure 2.1. *Advanced driving simulator of the University of Leeds. Source: Merat et al., (2012).*

Studies about driver behaviour in highly automated vehicles are conducted in simulators and not on the open road for two reasons: (1) In simulators devices and systems can be tested that do not yet exist, and (2) When participants commit errors or mistakes during transition of control, they will not get injured or killed, nor can participants injure or kill other road users.

2.4. Paradigms in driver behaviour theories and their possible effect on performance during transition of control

2.4.1. *The human factors paradigm*

The dominant paradigm to study how drivers behave in highly automated vehicles and what happens when drivers switch to manual driving is the human factors paradigm, based on cognitive psychological theories about human behaviour. The recurring theme in this paradigm is information processing. Information is processed in a sequence of stages, such as perception, recognition, prediction, decision, response selection and task execution, which are all interrelated. Situation awareness and mental workload are important concepts in these theories that try to explain the cognitive processes when humans drive.

Drivers that are aware of their situation know at any moment in time which aspects in the traffic environment are relevant for them. Endsley (1995) describes situation awareness as "The perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future." Within the model of situation awareness three levels can be distinguished: perception (SA level 1), comprehension (SA level 2); and projection (SA level 3). In terms of awareness of the traffic situation, level 1 is the ability to perceive aspects that could be relevant for road safety. A driver actively searches for stimuli that could intervene with her or his goals. Perception means that stimuli in the environment draw the attention of the driver because they arouse feelings that things are happening that may be important without being exactly defined. Level 2 is the recognition of the traffic situation based on aspects detected in the traffic scene. For the understanding of the present situation, the driver retrieves knowledge from semantic memory, such as rules of the road, and past experiences in situations like this from episodic memory. For the understanding of the present situation the driver also assesses the speed and direction of other road users in the scene. Level 3 is the driver's prediction about the development of the recognized traffic situation. These predictions are also based on knowledge stored in declarative memory and assessment of elements in the present situation (e.g. speed and direction of other vehicles in the scene). Although 3 levels are distinguished in situation awareness, these levels are interrelated. Being aware of the situation is the same as having a holistic comprehension of the situation.

There is no universally accepted definition of mental workload. De Waard (1996) argues that three interrelated concepts are important. These concepts are task demands, mental workload and effort. Task demands are determined by goals that have to be reached by performance. Mental workload is the result of reaction to task demands; it is the proportion of the mental capacity that is allocated for task performance. Effort is the voluntary mobilisation process of mental resources. He defines mental workload as

the "specification of the amount of information processing capacity that is used for task performance" (De Waard, 1996; p. 15).

When drivers drive in highly automated vehicles, it is assumed that their workload is low in relation to the driving task, because they only have to supervise the systems that perform the driving task. Because the workload is low their situation awareness will decline. It will take some time after transition of control before the driver fully reactives the situation awareness. *Figure 2.2* visualizes the effect on performance, mental workload and the degree of automation.
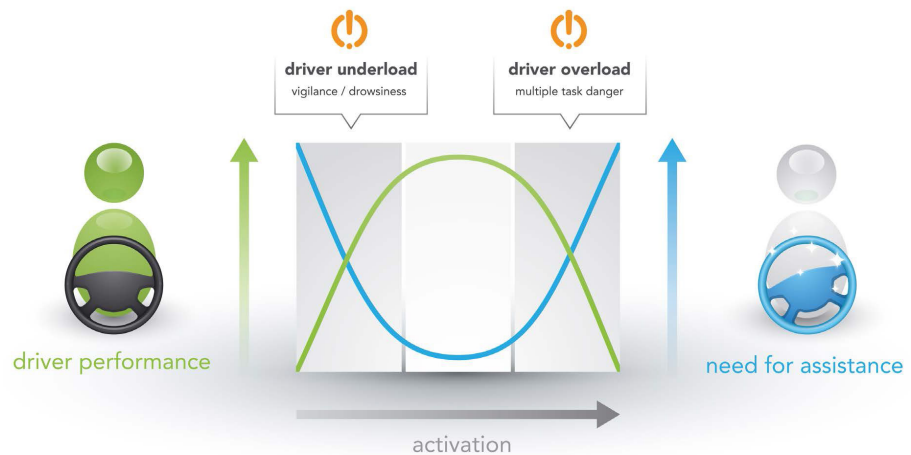

Figure 2.2. *The function between mental workload, performance and automation (Hoeger et al., 2008).*

In situations when the mental workload (depicted as 'activation' in *Figure 2.2*) is low due to automation of the driving task, the performance of the driver (the information processing and situation awareness) is also low. This is the situation on the left in *Figure 2.2*. When the driver suddenly has to resume the manual driving task there is an overload that is not supported by the automated systems that support the d (the right side in *Figure 2.2*) river.

There are indeed a multitude of studies that show a diminished situation awareness when the mental workload is low due to systems that support the driver or even take over the driving task (Barnard & Lai, 2010; Carsten et al., 2012; Jamson et al., 2013; Jamson et al., 2011; Merat & Jamson, 2009; Merat et al., 2012; Muhrer, Reinprecht & Vollrath, 2012). Drivers start to do other things not related to driving and or they get drowsy, which results in a drop of total mental capacity (Young & Stanton, 2002; Young & Stanton, 2007). Endsley and Kiris (1995) have referred to this diminished situation awareness as being 'out-of-the-loop', due to the level of automation. How being out-of-the-loop affects driving performance after drivers have switched to manual driving is discussed in *Chapter 3*.

2.4.2. *The motivational paradigm*

Theories and studies based on the human factor paradigm show and explain that drivers have reduced situation awareness when the workload is low and they mainly have to supervise automated systems. Human factors studies

do not explain why drivers tend to trust automated systems and experience diminished feelings of risk when systems perform the driving task. The faith drivers have in the automated systems and the feelings of risk that are experienced while driving in the fully automated mode are studied within the motivational paradigm.

Drivers tend to lose situation awareness more quickly when they trust the system; they tend to trust the system when they are of the opinion thatthe system shares their intentions (Verberne, Ham & Midden, 2012). Feedback of the system (what it is doing and why it is doing) also helps to trust the system. When drivers do not trust the system and the vehicle drives in the fully automated mode, stress will increase and stress may affect the mental workload of the driver (Stanton & Young, 2000). Therefore both overconfidence and lack of trust may have a negative effect on risk-awareness and self-awareness when the vehicle switches from the fully automated mode to the manual mode.

Another issue within this paradigm is 'locus-of-control'. Passing control from the driver to the system strengthens external locus-of-control, because the driver can no longer influence the manner in which the task is executed (Parasuraman, 2000). People with a strong external locus of control tend to blame others or the circumstances for negative events that happen to them whereas people with strong internal locus-of-control think that events primarily derive from their own actions. Drivers with a strong external locus of control will blame others and the circumstances when they are involved in a crash and drivers with a strong internal locus of control will blame themselves when they are involved in a crash. Studies have shown that drivers with high levels of external locus of control and low levels of internal control have more crashes than drivers with low levels of external locus and high levels of internal locus (Huang & Ford, 2012; Montag & Comrey, 1987).

2.4.3. *The dual processing paradigm*

There are also theories about driver behaviour that are based on the functioning of the brain. In these theories a distinction is made between automatic human processing of information and controlled human processing of information (Evans, 2008; Kahneman, 2011; Shiffrin & Schneider, 1977; Slovic et al., 2004). In these theories mental structures that are called schemata play an important role. Schemata enable drivers to understand the traffic situation without much mental effort. These theories also explain that higher-order driving skills, such as hazard perception, can be diminished just after transition of control because the proper schemata are not activated in the brain.

Norman and Shallice (1986) have developed a dual processing theory about the way in which drivers process information when they execute the driving task for instance. A crucial element in their theory is the notion of *schemata* According to Shallice (1988), at its lowest level, a schema is a mental representation of a sequence of well-learned actions. They help to do something when particular circumstances arise. When, for instance, a driver approaches an intersection and the traffic light turns red, the schemata for braking when traffic lights turn red will be activated and will help the driver to perform the sequence of actions more or less automatically. The schemata that control steering a car require visual-spatial and manual processing

systems and also appropriate recognition systems. Connected low-level schemas constitute high-level schemata. These high-level schemata are mental structures that organize our knowledge and enable us to make assumptions about something we perceive. They help us to cope with the world without too much mental effort. If we had to think about everything we are doing all the time and had to weigh all possible actions all the time before we decide to do something, we would soon be exhausted. Schemata influence our selective behaviour, because we are more likely to notice or react to things that are anticipated by our schemata. Wrong activated low-level schemata or not well-elaborated high-level schemata can lead to a misinterpretation of the situation. At the highest level, schemata are 'scripts' (Abelson, 1981; Schank & Abelson, 1977) or 'Memory Organisation Packets' (MOPs) (Schank, 1982). One such a script or MOP could be 'the driving on a motorway' script or MOP. This script is a conceptual structure of how to behave (stereotypical sequences of action,e.g. driving at a relatively high speed in the same direction as the other vehicles) and what to expect (e.g. no passengers that cross the road, no oncoming vehicles) when driving on a motorway.

The model of Norman and Shallice (1986) is based on two assumptions:

– *Routine actions are based on schemata.* The selection and activation of schemata for routine actions is decentralised and thus require no central control. The relatively automatic selection, activation and inhibition of low-level schemata in routine situations is called Contention Scheduling (CS). Stimuli in the situation perceived trigger schemata and schemata can switch each other on and off. The latter is called lateral facilitation and inhibition of schemata: the combined automatically activated low-level schemata and the automatically inhibited low-level schemata from the selected dominant high-level schema for a particular moment in time. These high-level schemata constitute the 'default option' for action in familiar situations;
– *Non-routine actions require conscious interference in the more or less automatic process of contention scheduling.* In non-routine situations, schemata have to be inhibited that were selected by the Contention Scheduler (CS) and schemata that were not activated by the CS have to be activated. This requires conscious attention and is carried out by a system called the Supervisory Attentional System (SAS).

Figure 2.3 is a simplified representation of Norman and Shallice's model on willed and automatic control of behaviour.
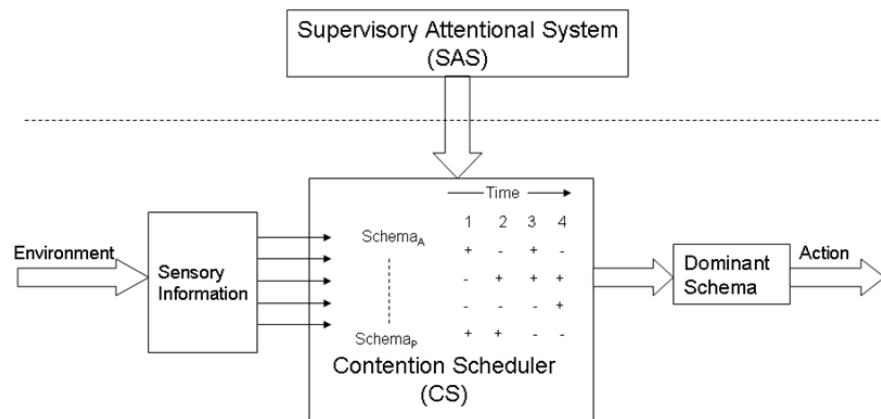
Figure 2.3. *Simplified schematic representation of Norman and Shallice's model on willed and automatic control of behaviour (adapted from Norman & Shallice, 1986).*

Drivers perceive the environment (the road, the (weather) conditions, other road users, the status of their vehicle (speed and direction), but also their own internal status (constitution, skills, feelings and emotions). This is depicted in *Figure 2.3* by the box 'Sensory Information'. Schemata are automatically triggered when certain conditions are met. One schema can also select or inhibit another schema (lateral facilitation and inhibition between schemata). As already mentioned, the automatic process of the selection of schemata is, called contention scheduling (CS). In *Figure 2.3* schemata that are activated at a particular moment in time (e.g. at moment 1) are marked with a '+', those that are inhibited at that particular moment in time are marked with a '-'. The lower schemata selected constitute one overarching dominant schema for that moment in time. The dominant schema selected structures what the driver perceives, recognizes and expects in this case. This enables certain actions being performed.
In contrast to the CS, the SAS reflects explicit thoughts about the environment and internal states of the driver. It is involved in the start of actions willed and situations required when the outcome of the CS is unsatisfactory. According to Shallice (1988), the SAS is invoked when coping with new situations, when (deliberate) decisions have to be made between various options, in overcoming temptation or in dealing with danger. The SAS operates indirectly by modulating activation within the CS. This is to say that the SAS activates schemata (turn a - into a +) or inhibits schemata (turn a + into a -) within the CS. This consciously turning off and on of schemata requires attention. For Norman & Shallice (1986) attention is only associated with top-down activation and inhibition of schemata, but not with the selection of the dominant schema.

Supposing a driver approaching an intersection and the traffic light turning yellow. This situation automatically triggers the default schema 'decelerate in order to stop before the traffic light'. Now also suppose that the driver is in a hurry. The yellow traffic light now becomes a salient event that interrupts his goal (arriving somewhere in time). The monitor inhibits the ongoing behavioural intentions (actions for decelerating) and switches on the SAS. The SAS intervenes in the CS and the default dominant schema 'decelerate in order to stop before the traffic light' is changed into the dominant schema 'accelerate in order to pass the intersection before the traffic light turns red'.

The interference of the SAS in the CS is depicted in *Figure 2.3* by the vertical arrow between the box that depicts the SAS and the box that depicts the CS.

With regard to transition of control, the theory of Norman and Shallice (1986) predicts that a driver who trusts the system and is involved in other tasks not related to driving when the vehicle is in the fully automated mode, will no longer keep the driving schemata activated. When the driver suddenly has to resume the driving task, the SAS is activated. However, not all relevant schemata are activated immediately. This may result in an incomplete mental representation that allows drivers to comprehend and to predict the traffic situation. This implies reduced hazard anticipation after transition of control. There are indeed indications that not all the relevant schemata are switched on immediately after transition of control. For instance, Skottke et al. (2014) found that drivers who had been in a platoon with very short headways in which they did not have to drive themselves, kept on driving close up to the lead vehicle for a while after they had to drive manually again. Phenomena like this are called habitual adaptation. The drivers presumably were so used to have a lead vehicle just in front of them while they did not having to drive that they did not immediately experienced the danger of too short a headway when they resumed driving.

2.5. Conclusions

Although automation is beneficial in many instances, including road safety, there are some human factors that have a negative effect on road safety. These negative effects occur when vehicles function as automated vehicles most of the time, but drivers have to switch to manual control occasionally. It has been found in several studies that situation awareness declines when the workload is low due to automation of the driving task. Drivers tend to rely on the automated systems and start to perform tasks other than driving (e.g. watching a movie). Automated vehicles may also strengthen internal locus of control and drivers with higher levels of locus of control tend to have more crashes. Dual processing theories predict that drivers do not keep schemata activated that help them to perform the driving task while the vehicle is driving in the fully automated mode. This may hamper their hazard anticipation abilities after transition of control. It was found in one study that this resulted in hazardous behavioural habituation after transition of control.

3. Task execution directly after resumption of control: What do we know and what do we need to know?

3.1. Cognitive control levels that characterize the driving task

Until now, only a few studies have been conducted about what happens directly after regain of control by the driver. According to Michon (1979), there are three cognitive control levels that characterize the driving task: the *strategic level*, the *tactical level*, and the *operational level*. The strategic level includes planning of a trip, choice of the mode of transportation, choice of route and time of driving. An example of a strategic choice is taking the short route through the village instead of taking the longer but easier route around the village. On the tactical level, drivers amongst others choose their cruising speed and headway. This implies considering optional manoeuvres such as overtaking in various road and traffic situations. Choices on the operational level concern the second-to-second execution of basic lateral and longitudinal control tasks of driving (steering, braking, gear shifting) required to keep the car in lane and to avoid crashes. The strategic level plays no relevant part during transition of control. However, the tactical level and the operational level do.

Only one study was found about the resumption of control on the operational level: 'Transition to manual: Driver behaviour when resuming control from a highly automated vehicle' (Merat et al., 2014).On the other hand, there are more studies about what happens in the first couple of seconds after regain of control at the tactical level. On this level a distinction can be made between dealing with acute threats and the anticipation of latent hazards. An acute threat may be a lead vehicle that suddenly brakes without cues that could have predicted this braking. Hazard anticipation can be defined as a set of driver behaviours that include the following: (1) awareness and knowledge of roadway risks and associated threats to driving safety; (2) visual search that facilitates detection and recognition of elements directly or indirectly contributing to unsafe situations; (3) prediction of emerging and latent hazards based on information from the visual scene; and (4) execution of driving responses to avoid or minimize potential conflicts due to recognized hazards (McDonald et al., 2015). This is the same as situation awareness for hazards in the road and traffic situation. A latent hazard is a possible hazard that will not necessarily develop into an imminent threat. Latent hazards may be other road users on a collision course blocked from view by, for example, large vehicles (lorries, buses), parked cars, hedges, or buildings. Drivers have to anticipate latent hazards, even though these hazards will not materialize most of the times.

With respect to acute threats, two studies were found on regain of control at the tactical levels:. 'Take over! How long does it take to get the driver back into the loop?' (Gold et al., 2013) and 'How do drivers behave in a highly automated car?' (Merat & Jamson, 2009). Regarding latent hazards, no studies were found on hazard anticipation directly after resumption of control. However, 'The effects of momentary visual disruption of hazard anticipation and awareness in driving.' (Borowsky et al., 2014), studied the detection of latent hazards in the first seconds when drivers turned their

attention to the road again after having been engaged in a secondary task not related to driving. Although this study does not concern regain of control in highly automated vehicles, it deals with the effect a disruption of the driving task may have on hazard anticipation regarding latent hazards.

For reasons mentioned in *Section 2.3*, all the studies mentioned in this section were simulator studies. How these studies were conducted and what the results of these studies are will be discussed in *Section 3.2* of this chapter.

3.2. **Studies about task execution directly after resumption of control**

In an advanced driving simulator (the simulator depicted in *Figure 2.1*) Merat et al. (2014) conducted a study about transition to manual driving at the operational level. Participants had to resume control over the automated vehicle while driving on a motorway. At the certain moment in time during the drive a variable message sign (VMS) appeared with a message that there was a stranded vehicle ahead and three lanes had merged into one. Participants of this study knew they had to resume the manual driving task when these signs appeared. It was investigated how long it took before participants had switched to manual and had acquired full control over the vehicle. Measures for vehicle control were the standard deviation of the lateral position (SDLP) and the frequency of steering adjustments. There were two conditions: (1) moments when a switch to manual driving was required while drivers were attentively scanning the forward roadway while the vehicle was in fully automated mode, and (2) at moments the eye-tracking equipment indicated that drivers were not attentively scanning the forward roadway while the vehicle was in the fully automated mode. When drivers were attentive, switching to manual and regaining proper control over the vehicle took on average 10 s. When drivers were less attentive when driving in the fully automated mode, switching to manual and regaining full control over the vehicle took circa 35-40 s. These results imply that especially when drivers are not attentive, messages about a switch to manual must be provided properly and timely. These results also indicate that planned switches to manual driving have to occur in traffic situations where crash risk is low.

3.2.1. *Transition of control at the tactical level and acute hazardous situations*

Gold et al. (2013) conducted an experiment in an advanced driving simulator in which participants drove on a motorway. During their drive, participants had to follow a lead vehicle. This lead vehicle suddenly turned to the left lane and a stranded vehicle in the middle of the lane became visible. To avoid a collision, participants had to brake and to swerve around this stranded vehicle. There were three groups: (1) a group that drove manually, (2) a group in which the vehicle was in the fully automated mode and the driver was attentive. Just after a participant had switched to manual driving, the lead vehicle turned to the left and the stranded car became visible, and (3) a group in which participants were engaged in a secondary task while the vehicle was in the fully automated mode. As in the case of the second group, the participants in this group had to switch to manual driving and directly after this moment, the lead vehicle turned to the left and the obstruction became visible. The gazing procedures (e.g. looking in the side mirror), the handling procedures (e.g. provide a turn signal), and the manoeuvres to

avoid a collision were carried out much better in the manual group than in the group that had been driving in the fully automated mode, even though they were attentive. A comparison between the attentive and inattentive drivers in fully automated mode showed a better performance of the attentive group than the inattentive group.

In a further simulator study, using the advanced simulator depicted in *Figure 2.1*, drivers were required to regain control of the driving task if the automated system was unable to handle the critical situation (Merat & Jamson, 2009). This study was conducted for the EU-funded CityMobil project. When the system was no longer able to perform the driving task, an alarm sounded, prompting the driver to resume manual driving. Around 3 s after resumption the lead vehicle suddenly braked. There were two groups: a group that had to switch to manual driving and a group that drove in the manual mode during the entire simulator drive. Drivers' response to the sudden braking of the lead vehicle was significantly slower in the group that had been driven in the automatic condition, compared to the group that had been driving manually during the entire trip. This shows that automatic driving lengthens the response latency even in situations in which the driver has shifted to manual driving seconds before the hazard emerges.

These two studies indicate that there is response latency in acute critical situations when drivers have just switched to manual driving. This latency lasts longer when drivers do not pay attention to the driving task when the vehicle operates in the fully automated mode. These results also imply that messages about a switch to manual are provided properly and timely and that planned switches to manual driving should occur in traffic situations with no acute threats.

3.2.2.   *Resumption of the driving task in situations with latent hazards*

In a simulator study conducted by Borowsky et al. (2014) participants drove while an eye-tracking system recorded their gaze directions. During their drive, participants had to perform a secondary visual task that required them to take their eyes of the road. At the moment they looked up again they drove in a traffic situation that contained a latent hazard, namely a T-intersection in which the view on a possible approaching vehicle at collision course was blocked by a parked lorry. Eye movement analyses showed that drivers who had been interrupted by a secondary task often failed to scan for a latent hazard directly after interruption, especially when the latent hazard was difficult to locate.

Although this study was not about driving highly automated vehicles, because participants still had to drive manually, its results indicate that situation awareness for latent hazards may be severely diminished after being interrupted.

3.3.   **What do we know and what do we need to know?**

The studies reviewed unanimously indicate that when drivers are passengers in their own vehicle and have to resume the driving task while the vehicle is driving, task execution is temporarily impaired both at the operational level and the tactical level of cognitive control. It seems that situation awareness is more affected when drivers are involved in other

activities before they have to resume the driving task compared to drivers that remained actively scanning the forward roadway while they did not have to drive.

We have found some indications about the duration of the impairment at the operational level and the influence of the state of the driver (attentive or inattentive with regard to driving task) on this duration. However, we know very little about how long situation awareness is reduced with regard to acute threats and no studies were found about the duration of reduced situation awareness for latent hazards.

There are planned moments when the driver has to switch to manual driving (e.g. when automatic driving is only possible on motorways and the driver wants to leave the motorway) and there are acute moments when the driver has to resume to manual driving (e.g. when the system fails or the system cannot manage the traffic situation). In case of a planned switch, there is time to change the state of the driver (i.e. from out-of-the-loop to in-to-the-loop) before the driver resumes manual control over the vehicle. So far, little is known about the optimum way to do this (e.g. combinations of an auditory alarm, blinking displays, a confirmation button, et cetera).

We do not know how trust in the system influences transition of control. So far all studies about transition of control have been simulator studies. The reason is that there are no level 3 vehicles yet and it is unethical to conduct studies on the open road, because we do not know how dangerous transition of control actually is. Trust in the reliability of the system will probably be different in a simulator than in a real vehicle in real traffic. It is unethical to test loss of situation awareness and its duration on the open road with regard to acute threats, but it can be done with regard to latent hazards because they do not have to materialize.

The conclusions and considerations mentioned result in the following subjects for further research:
− Duration of diminished situation awareness after resumption to manual driving regarding acute threats and in particular regarding latent hazards;
− The influence of the driver state (e.g. attentive or inattentive) while driving in the fully automated mode on the duration of the diminished situation awareness directly after transition of control;
− The optimum interface to turn drivers who are out-of-the-loop to in-to-the-loop just before transition of control, and
− The influence of trust in the system on the severity and duration of loss of situation awareness regarding latent hazards in real traffic.

4.   Conclusions and recommendations

4.1.   Conclusions

The future development of fully automated vehicles cannot yet be fully predicted. Most probably an increasing number of automated vehicles will enter into our roads and have to mix with other traffic. Vehicles will not all be at once the fully automated vehicles in the way the Google car is automated. There will be a mixture of vehicles with different levels of automation and this will gradually change into a mixture of vehicles with higher levels of automation becoming dominant.

From levels 2 to 5 in the taxonomy about degrees of vehicle automation as developed by SAE, drivers will sometimes be passengers in their own vehicle and sometimes have to resume to manual driving while they are in traffic. This switch is referred to as 'transition of control'. There can be sudden moments when drivers have to switch to manual and there can be planned moments when drivers have to switch to manual driving.

Although the automation of the driving task will be beneficial for road safety, drivers in highly automated vehicles sometimes suffer negative consequences of automation, such as loss of situation awareness, complacency and automation surprises. An automation surprise is an action that is performed by an automated system that is not expected by the user. These negative consequences will create new hazardous situations for drivers, especially when drivers have to change roles from being a passive passenger in their own vehicle to an active driver that manually controls the vehicle.

The mental processes and how these processes can affect driver behaviour during and just after transition of control can be explained by different theories about driving. Theories based on attention and cognitive information processing predict that the driver will experience a loss of situation awareness for the traffic situation while he is not actively driving and that it takes some time after resumption of the driving task that situation awareness is fully recovered. There are indeed a multitude of studies that indicate diminished situation awareness when task demands regarding the driving task are low due to automation. There are also some studies in which it was found that situation awareness for acute dangerous situations is diminished directly after resumption of the driving task. This increases when the transition of control occurs suddenly and the driver had not paid attention to the driving task just before attention of control. Not only is the situation awareness affected at the tactical level of control, but also the performance at the operational level (the longitudinal and lateral control over the vehicle).

Motivational theories about driving have shed light on the effects of trust in the automated system on driving behaviour. When too much trust is placed in automation, a false sense of security will arise and will result in a loss of risk-awareness.

Dual processing theories predict that when the vehicle is driving automatically, pathways in the brain will no longer activate schemata that

SWOV publication R-2015-22

enable drivers to develop mental representations which help them to recognize the traffic situation, to predict what may happen and to act quickly. After resumption of control over the vehicle, the slow error-prone supervisory attentional system will be active in the brain before 'normal' driving can resume. These theories also explain why behavioural habituation may occur. For instance, it was found in one study that drivers kept driving close to a lead vehicle after the platoon of automated vehicles had terminated.

The following subjects of further research were identified:
− Duration of diminished situation awareness after resumption to manual driving regarding acute threats and in particular regarding latent hazards;
− The influence of the driver state (e.g. attentive or inattentive) while driving in the fully automated mode on the duration of the diminished situation awareness directly after transition of control;
− The optimum interface to turn drivers who are out-of-the-loop to in-to-the-loop just before transition of control, and
− The influence of trust in the system on the severity and duration of loss of situation awareness regarding latent hazards in real traffic.

4.2. Recommendations for vehicle, road, and driving licence authorities

It is important to note that although much is known about how humans interact with automated systems not much is yet known about transition of control in highly automated vehicles. Although it is safe to conclude that the brief periods of transition of control are likely to affect road safety, we still do not know which skills are temporarily affected and for how long. We neither have a complete picture yet of the transient factors that instantaneously reduce the driving capabilities due to transition of control. Because of all these unknown factors, the recommendations in this section should be understood as possible measures that could become relevant for implementation, when more will be known about the behavioural aspects of transition of control.

4.2.1. Recommendations

It is recommended that vehicle authorities ascertain that only those highly automated vehicles are allowed to drive on our roads in which abrupt switches are reduced to the bare minimum. In contrast to abrupt switches, planned switches allow for getting the driver in-the-loop again before he has to resume the driving task. Systems that are robust and function flawlessly in all traffic situation, road conditions and weather conditions will need less acute switches of control than error-prone systems. It is also advantageous to have back-up systems installed in the vehicle that will take over when the first system fails. It will allow other road users to anticipate possible mistakes by a driver who is switching to manual driving when the other road users can observe (e.g. by a sign on the vehicle) that the driver of the automated vehicle is switching to manual driving.

Until now, little is known about how to get the driver successfully back in-the-loop just before transition of control. It seems that much depends on the human-machine interface (type of alarm, visual information on the display, confirmation button, et cetera). To optimize the process of getting the driver in the loop as soon as possible, the system also has to assess the state of

the driver adequately. In short, guidelines are required for the human-machine interface during transition of control.

When planned transitions of control occur at known locations (e.g. at spots where vehicles can leave the motorway and automated driving is only possible on motorways) these locations should be arranged in such a way that hazards cannot occur. For instance, no other vehicles should be allowed in the vicinity of the fully automated vehicle in which the driver has to switch to manual.

It is not very likely that drivers can be trained to actively scan the traffic situation and to remain vigilant when they do not have to drive for a considerable period of time. It is to be recommended that driving licence authorities take such measures that drivers retain the skills they need when they have to drive manually. In aviation, pilots are required to fly manually regularly, despite the fact that the system can perform the flying task better than the pilots. Pilots also have to train rare and difficult procedures in a flight simulator repeatedly.

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