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Road vehicles — Human performance and state in the context of automated driving —

Part 2: Considerations in designing experiments to investigate transition processes

Véhicules routiers — Etat et performance humaine dans le contexte de la conduite automatisée —

Partie 2: Principes expérimentaux pour étudier les processus de transition

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Foreword

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Introduction

Although automation technology is advancing at a rapid pace, the majority of automated driving levels (as defined by SAE J3016, 2016[1]) still require a human to fulfil specific remaining (driving related) tasks. The safety-critical human's task is the takeover task in transition from a higher level to a lower level of automated driving. Researchers and developers continue to seek system design and human machine interface improvements for better takeover performance. Researchers face a challenge in understanding the limitations of a human's ability to perform the takeover task, which involves different human factors. Developers work to evaluate systems to see whether the takeover process is effective at minimum risk in specific scenarios. There are a wide variety of experiments to evaluate takeover performance in transition for many different purposes. This document contains information to consider in the takeover scenario, some of which is still under investigation, in order to help readers design experiments to evaluate takeover performance and design appropriate experiments.

Road vehicles — Human performance and state in the context of automated driving —

Part 2: Considerations in designing experiments to investigate transition processes

1 Scope

This document focuses on system-initiated and human-initiated transitions (Clause 6) from a higher level to a lower level of automated driving. Human factors and system factors that can influence takeover performance are included (Clauses 7 and 8). Although some are still under investigation, there is a need to appropriately set these factors as variables to better understand their effects or to better control/eliminate their influence. This approach will aid research design by ensuring that important factors are considered and support consistency across studies enabling meaningful comparisons of findings. This document also includes information on considerations in test scenario design (Clause 9), common measures for human takeover performance (Clause 10) and considerations in choosing a testing environment (Clause 11) to help readers design experiments comparable to other studies.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

4 List of Acronyms

DDT	Dynamic Driving Task
DMS	Driver Monitor System
ECG	Electrocardiogram
EEG	Electroencephalogram
HMI	Human-Machine Interface
KSS	Karolinska Sleepiness Scale
MRM	Minimal Risk Manoeuvre
NDRT	Non-driving Related Task

NDRA	Non-driving Related Activities
OEDR	Object and Event Detection and Response
ODD	Operational Design Domain
RtI	Request to Intervene
SAGAT	Situation Awareness Global Assessment Technique
SDLP	Standard Deviation of Lateral Position
SIMS	Situational Motivation Scale
SuRT	Surrogate Reference Task
TLC	Time to Lane Crossing
TTC	Time-to-Contact/Collision

5 Purpose

The purpose of this document is to provide considerations in designing experiments to measure human takeover performance in transition situations in order to better understand human limitations, evaluate systems, and improve systems, including human machine interfaces. This document is expected to help users design appropriate experiments for their purposes. This document does not provide any design principles to restrict or direct the system design.

6 Transition process models

6.1 General

Transition processes included in this document are generally based on the models defined in ISO/TR 21959-1[2]. A human's safety-critical task is the takeover task in transition from a higher level to a lower level of automated driving both for system-initiated and human-initiated transitions. ISO/TR 21959-1[2] defines typical transition process models from automated to manual driving (i.e. level 0). However, the models can be adapted for transitions between different levels (e.g. 4→2 or 3→1). This clause reminds readers of the relevant transition process models.

6.2 Transition process model for system-initiated transitions

In a system-initiated transition, the system may issue a request to intervene (RtI) when it finds a dynamic driving task (DDT) performance-relevant system failure or an object/event which cannot be handled by the system for levels 1–4. The system also may issue an RtI when exiting the operational design domain (ODD) for which it was designed, (e.g. exiting a motorway, exiting assumed environmental conditions such as weather and traffic). The driver is expected to take over the DDT in response to an RtI to continue driving. The system may terminate immediately after issuing an RtI for level 2 while it shifts to the takeover mode following an RtI before termination for levels 3 and 4 (Figure 1). There can also be other types of transitions after an RtI, such as transitions from level 2 to level 1 and from level 3 to level 2. The driver's task model can be adjusted depending on the level after the RtI (i.e. object and event detection and response [OEDR] task for transition to level 2, OEDR task +lateral control or OEDR task +longitudinal control for transition to level 1). When the driver does not initiate intervention within the takeover mode, the system may shift to the minimal risk manoeuvre (MRM) to stop the vehicle safely for level 3 and level 4 (see 8.2.2 for details).

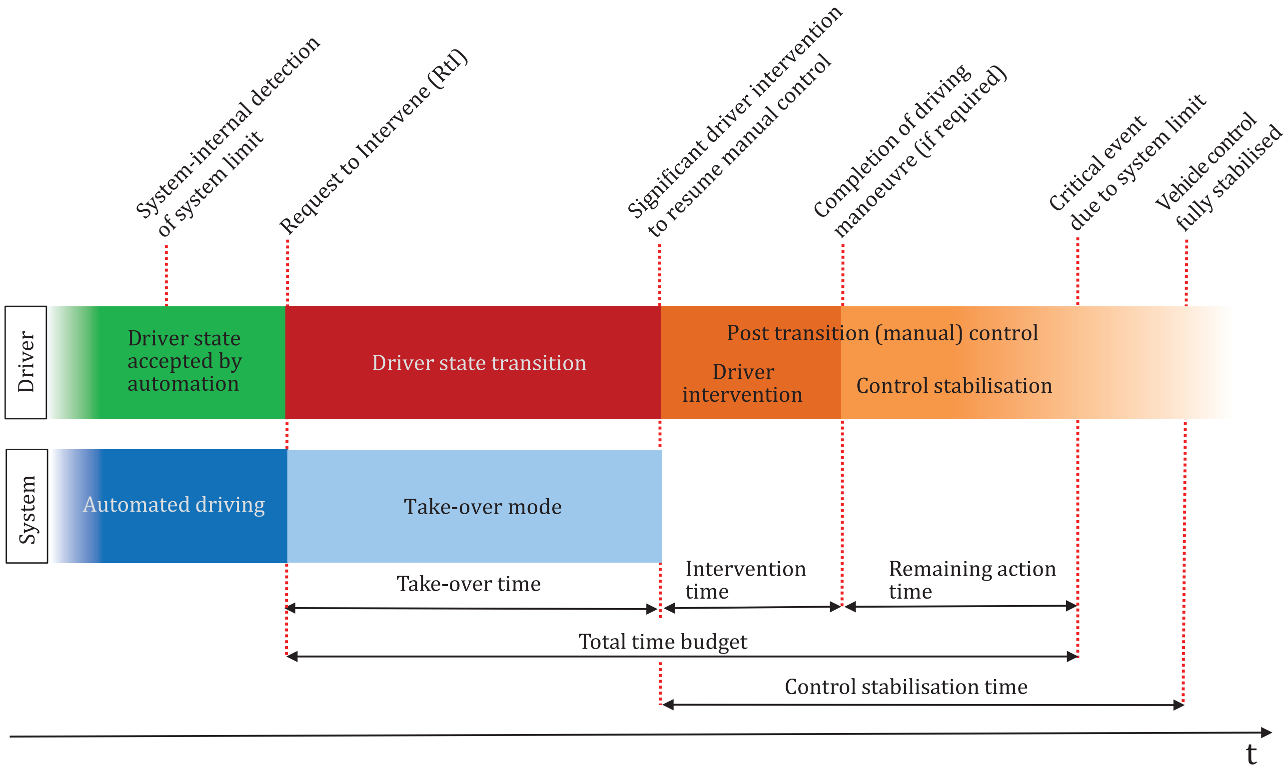

Figure 1 — Transition process model for system-initiated transitions from automated to manual driving

6.3 Transition process model for human-initiated transitions

The driver is authorized to take over the DDT at any point during operation of the automated driving functions, except for some level 4 and level 5 features some or all of the time. The human-initiated transition may be either optional or mandatory. The optional case is the transition where the user wishes to drive manually without being in a safety critical situation. The mandatory case is the transition where the level 2 system fails to avoid an undetected object/event due to the system's functional limitations or where the system suddenly terminates without issuing an RtI due to a DDT performance-relevant system failure. In such mandatory transitions, the driver is expected to detect the object/event or the failure and initiate transition (Figure 2). This type of transition is mainly from level 2 to manual driving but can be from level 2 to level 1. The driver's task model can be adjusted depending on the level after the initiation.

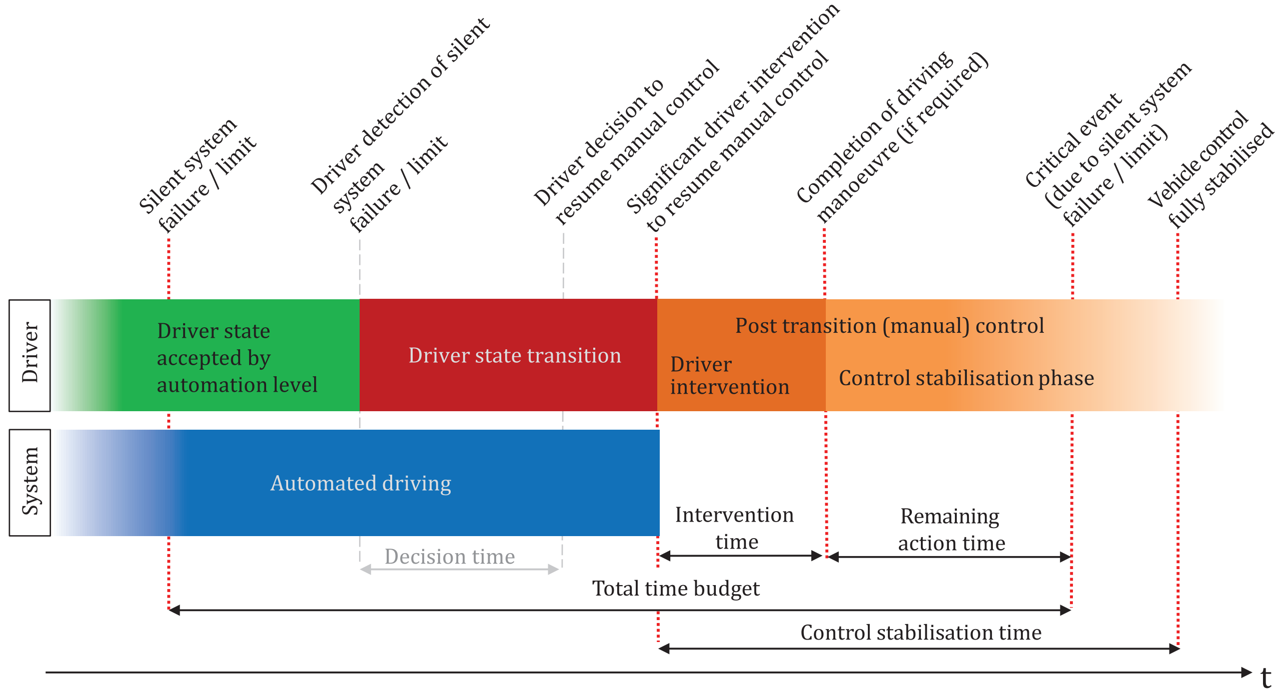

Figure 2 — Transition process model for mandatory human-initiated transitions from automated (level 2) to manual driving due to driver's detection of a safety-critical object/event or a DDT performance-relevant system failure

7 Human factors that influence takeover performance

7.1 General

It is known that a driver's takeover performance varies with the influences of multiple factors. In experiments, there is a need to appropriately set factors as variables for investigating their effects or better controlling/eliminating their influence. This will allow for the design of experiments that are easier to compare with other studies. This clause presents information about "internal" human factors that may influence a driver's takeover performance. Driver's takeover performance includes time in the driver state transition phase (i.e. response time of significant driver intervention to RtI) and quality in the post transition control phase (i.e. how well the driver controls the vehicle right after the significant driver intervention; see also Clause 10).

7.2 Driver attributes

7.2.1 Knowledge

Drivers' knowledge about system functions, limitations and the required driver's role, has been found to influence takeover performance in some studies[3][4][5]. Other studies have found that instructions have limited effects[6][7]. In general, the sources of a driver's knowledge are diverse and may include mass-media, instruction manuals, instructions given at a car-dealership and other various sources. In experiments, such knowledge can be controlled, to some extent, by screening subjects using questionnaires investigating their level of a-priori knowledge and by providing them with controlled information about the functions, limitations and driver's role for the specific system of study. It is to be noted that difficulty in forming a detailed picture of subjects' exact knowledge obtained from various sources for various systems may lead to some variation in the results of takeover performance. In some instances, participants may have incorrect knowledge about system function, limitations and the required driver's role leading to misbehaviour or misuse.

7.2.2 Experience and trust

A driver's experience with using the system has been found to influence takeover performance. How the driver has previously interacted with the system may influence performance in different ways as a result of different levels of understanding and trust. Short term system interaction experiences may lead to a better understanding of the system's functions and limitations and better trust calibration, resulting in better driver takeover performance[8][9][10][11][4][5]. Longer-term experience with no to a few system disengagements may lead to a driver's over-trust of the system and complacency[12], which can degrade takeover performance[6]. In contrast, longer-term experience with too many system disengagements may lead to driver under-trust, which might improve takeover performance[13] but which also may lead to disuse of the system[14]. In experiments, such experiences can be controlled, to some extent, by screening subjects using questionnaires investigating their experiences with specific systems featured in the study and the frequencies of the interactions they have experienced. After screening, new subject experience can be introduced by providing subjects specific driving conditions after providing controlled interactions. It is to be noted that similar systems with the same level of automated driving can differ in functions and limitations (i.e. detection targets, ODD, reliability and others) by brand or even by different models within one brand. Also, different users of the same brand system may use the system in different ways in different traffic environments. Therefore, experience still may lead to some dispersion in the results.

7.2.3 Demographic attributes

7.2.3.1 Age

A driver's age-related perceptual, cognitive and physical limitations may influence takeover performance. Visual impairments of older drivers are diverse and are often accompanied by eye diseases[15]. Such impairments may degrade perception of traffic environment in the OEDR task or in the process of transition. Visual impairments may also cause difficulty in reading system status information displayed in the cockpit[16]. Cognitive impairments may degrade understanding of "complicated" system functions/limitations and the driver's role. These impairments may also lead to problems with divided attention[17] and slow down task switching in transitions. Physical impairment may degrade speed and accuracy of the response behaviour in transitions. Although, as mentioned above, there are several hypotheses for older drivers' degraded takeover performance, the effects of age are still under discussion. Some researchers have found significant negative effects of age[18][19][5][20][21], whereas other researchers found only limited effects[22][23]. In experiments, subjects can be screened not only based on age but also based on the results of perceptual, cognitive and physical response tests. However, it is to be noted that the effects of age have large inter/intra-individual variability and still may lead to some dispersion in the results of takeover performance of subjects who were screened via tests.

7.2.3.2 Other demographic attributes

There are other driver demographic attributes that may influence takeover performance, such as experience and skill of manual driving, style of manual driving with individual and cultural differences, technology-sensitivity and general trust of technology. However, these factors have not yet been well studied.

7.3 Driver readiness/availability

Conceptually, readiness/availability is a driver's dynamic state during automated driving, which influences their takeover performance. Readiness/availability can be continuous; lower readiness/availability than a required level may lead to degraded and unsafe takeover performance[24][25][26][27][28] (see also A.2.2). Considering the definitions of the driver's role for each level of automation, the required level of readiness/availability generally increases with decreasing levels of automation. The readiness/availability is considered to include several components related to motoric/physical and cognitive states (Table 1). Each component can have different metrics and different effects on takeover performance. The required level for each component of readiness/availability can be experimentally determined as the level that leads to a successful takeover by comparing the metrics and the takeover performance in time and quality in certain traffic conditions for a specific system transition design (see also A.2.2).

Table 1 — Components of readiness/availability

Components of readiness/ availability	Motoric/physical state	Cognitive state
Sitting position	✔	—
Posture	✔ Hands/arms, feet/legs, trunk	—
Engagement in NDRAs	✔ Hands/arms, manual operation	✔ Visual Cognitive
Drowsiness	—	✔
Mind wandering	—	✔
Situation awareness	—	✔
Operating state/mode awareness	—	✔

7.3.1 Sitting position and posture

When the driver is away from the driver's seat and sitting at another location[170], a significant amount of time will be required to return to that seat. One study reported that a driver with a larger torso angled in a relaxed posture showed poor takeover performance[29]. It may require a certain amount of time to return to the appropriate driving posture from a relaxed posture with, for example, the backrest inclined backward. When there is a large space between the driver and the system controls, with the seat moved backward, the steering wheel moved upward and the legs and/or arms crossed, it may require even more time for the driver to return to the appropriate driving posture[23]. In experiments, the driver's position and posture can be controlled by setting the seat and the steering wheel in the desired position and also by instructing subjects (drivers) to assume a desired posture. When evaluating a driver's takeover performance in the naturalistic setting, the driver's position and posture can be monitored by video recording, steering-touch sensors, a seat pressure monitor[30], seat position sensors, steering position sensors and the seatbelt buckle switch.

7.3.2 Engagement in non-driving related activities

When the driver is engaged in a non-driving related activity (NDRA), such as using a laptop, reading a book, or operating a hand-held device using hand(s) off the steering wheel, it can take more time to take over than when the driver is in the appropriate driving posture with both hands placed on the wheel[25][29][23]. The larger takeover time may include the time required to place the item in a secured place before grasping the steering wheel[31]. When the driver performs takeover with one hand while holding an item with the other hand, the quality of takeover performance may be degraded due to inaccurate one-handed steering operation. Time can be also consumed when the driver is wearing glasses for an NDRA and takes them off for takeover or vice versa[23].

Engagement in NDRAs may induce driver's manual examination or other visual and cognitive loads that may influence takeover performance. Some NDRAs require interactive driver manual operation (e.g. selecting a function on a touch-panel). Texting also requires continuous manual operation. NDRA manual operations induce one-handed steering and also intensive visual load for accurate operation. A visually loaded driver may fail to sample environmental elements that are necessary to develop the appropriate situation awareness[32]. When looking down, the driver may fail/delay to detect an object/event that requires immediate driver-initiated takeover for a level 2 system. This inappropriate situation awareness may degrade the quality of takeover performance after an RtI. When the driver is cognitively loaded by an NDRA, insufficient attention allocated to the road environment may also degrade the quality of takeover performance. Degradation of quality of takeover performance can be an inappropriate manoeuvre (e.g. abrupt manoeuvre, inappropriate choice of manoeuvre) or a delayed response manoeuvre to an event[33][34].

A number of studies have investigated the effects of NDRAs on takeover performance. Effects of specific types of NDRAs (e.g. using a tablet, typing an email, reading news, watching a video, performing an auditory-vocal task) on takeover performance have been investigated by some researchers[35][36][37]. Some NDRAs were found to degrade takeover performance in either time or quality or both. Louw et al. (2019)[38] found that a driver engaged in a visual NDRA (the arrows task in a computer display) with a level 2 system showed degraded performance of the driver-initiated takeover for a “silent failure” due to inappropriate attention allocation. Zeeb et al. (2016)[36] found that NDRAs such as reading a news text and watching a video did not influence the response time of grasping the steering wheel after an RtI (i.e. motor processes were carried out almost reflexively), whereas the lateral control of the vehicle in the control stabilisation phase was significantly degraded. The findings of Zeeb et al. (2016)[36] were consistent with those of Kitazaki et al. (2019)[39] and Choi et al. (under review)[34], who found a visual-manual task using a surrogate reference task (SuRT) (ISO/TS 14198)[40] caused an abrupt steering manoeuvre to change the lane to avoid a stationary object after an RtI, resulting in unstable lateral vehicle control after changing lanes. Kitazaki et al.[39] and Choi et al.[34] also found that a cognitive load using the N-Back task[41] slowed down the steering manoeuvre after an RtI, resulting in a shorter minimum distance to the stationary object. In contrast, Radlmayr et al. (2014)[42] found similar effects of SuRT and N-Back tasks in increased collision rates in the high density traffic situation.

Positive effects of NDRAs have also been reported by some researchers. Automated driving may cognitively underload the driver[43], resulting in development of drowsiness and degradation of performance[36]. NDRAs may counteract the cognitive underload and maintain driver alertness. Neubauer et al. (2012)[44] found that drivers using a cell phone showed a faster braking response following transition to manual driving than drivers without NDRAs. Schömig et al. (2015)[45] reported that the drowsiness of drivers given a quiz task stayed low compared to those without the task.

NDRAs used in experiments can be selected from those that drivers are most likely to be engaged in[46]. Simple representations of the tasks, such as SuRT for the visual manual task and N-Back for the cognitive task, can be also used for the purpose of analysing the influences more systematically and in a standardized way. Video recordings of a driver's behaviour are useful to extract time slots where the driver is engaged in NDRAs and to identify NDRA types, especially in naturalistic studies. When using an electronic device for an NDRA, performance on the device (e.g. number of touches on the screen) can be used to measure extent of a driver’s engagement in the NDRA. Subjective measures, such as the rating scale for mental effort[47] and NASA's task load index[48] have been widely used to assess the driver’s workload to conduct the NDRAs, even though these measures do not provide continuous information and cannot be used unobtrusively. There are a number of studies investigating biometrics of readiness/availability of a driver engaged in NDRAs. Because a driver’s input on the primary vehicle controls cannot be used as a metric of driver states when driving with the automated system, a majority of studies have focused on metrics obtained from video recordings of the driver’s face. These studies included gaze behaviour, such as gaze distribution and eyes-off-road time, as well as eye movements, such as frequency of saccades, blink duration, blink frequency, Perclos and pupil diameter[24][49][50][26][51]. There are a number of other studies that have estimated NDRA effects for distracted driving[52][53][54][55][50].

Emotional attachment to an NDRA caused by high motivation to the NDRA[56] may also influence the takeover performance. Even after the RtI has been issued, the driver can be strongly motivated to continue certain types of NDRAs (e.g. typing an email, reading a new article) to finish a chunk of activity before takeover. Delayed glance movement from the NDRA to the front after an RtI may explain this effect. The motivation in a given situation can be subjectively assessed by the situational motivation scale[57].

7.3.3 Drowsiness

Automated driving may cognitively underload the driver, resulting in drowsiness and degradation of vigilance[58][36]. Drivers participating in driving simulator experiments tend to develop drowsiness more rapidly than those in on-road experiments[59]. Long driving durations and monotonous driving environments tend to lead to faster development of drowsiness[60]. Higher drowsiness levels correspond to a smaller amount of accessible cognitive resources. Therefore, it is a reasonable hypothesis that drowsiness can degrade takeover performance in terms of time and quality[61][36]. A drowsy driver may fail to detect an object/event that requires driver-initiated transition for the level 2 system. For system-initiated transitions, negative effects of drowsiness on takeover performance were reported by some researchers[62][39], whereas no significant effects were found by other researchers[63][64].

In experiments, subjects' drowsiness levels can be controlled to some extent by conducting experiments considering circadian rhythms, instructing subjects to control their length of sleep before the experiment, or adjusting the driving scenario's duration and level of monotony[65]. However, it is difficult to precisely control subjects' drowsiness levels. Subjective measures, such as the Karolinska sleepiness scale (KSS), have been widely used to assess drowsiness levels[66]. Some biometrics have also been used to measure drowsiness levels, including Perclos[67], blinking duration[68][21], visual scanning, and also some physical actions[69][70]. Electroencephalograms (EEGs) have been used to measure depth and type of sleep as well as micro sleeps during driving[71].

7.3.4 Mind wandering

Mind wandering means thinking about issues unrelated to the ongoing driving task. Mind wandering shifts a driver's attention to internal information[72] and may result in deteriorated takeover performance similar to that caused by drivers with insufficient attention to driving due to an NDRA or low arousal[73]. In general, mind wandering is more likely to occur when a subject's vigilance is low[74]. Therefore, long durations of automated driving and a monotonous driving environment are more likely to induce mind wandering[58]. Although it is difficult to actively manipulate a driver's mind wandering in experiments, some studies have used "thought-sampling methods," which are based on self-report or intermittent questions such as, "Just now, were you mind wandering?" as part of the experimental protocol[75][76]. Some biometrics have also been found for mind wandering, such as gaze direction, pupil size[77], electrocardiogram (ECG)[76] and EEG[78].

7.3.5 Situation awareness

Situation awareness (SA) is the perception of environmental elements and events with respect to time or space, the comprehension of their meaning and the projection of their future status[79] and models of SA have been developed for driving (e.g. Reference [80]). Understanding the traffic situation (e.g. positions and speeds of neighbouring vehicles) and road environment (e.g. number of lanes, road shape) can influence takeover performance in time and quality when selecting an appropriate driving tactic to cope with a critical event both in driver-initiated and system-initiated transitions[81]. This influence becomes larger when traffic is denser and the road environment is more complex[42][33]. An example use-case is a transition before an obstacle in the same lane with another vehicle in the neighbouring lane. The driver is expected to take over control of the vehicle and change lanes before or after the neighbouring vehicle, depending on the gap and the relative speed to the neighbouring vehicle. Insufficient situation awareness may delay the decision making for an appropriate lane change or may lead to a collision with the neighbouring vehicle due to an inappropriate lane change initiation. Strategic level of situation awareness may also be important. An example use-case is an instance where a driver engaged in a NDRA receives an RtI and takes over control of the vehicle without being aware of the current location on the route to the destination. The driver may not be properly prepared for taking a turn at a forthcoming intersection[82], which may result in a risky situation if the driver takes the turn too late or abruptly.

Situation awareness can be influenced by NDRAs, drowsiness and mind wandering as mentioned above. It can also be influenced by trust and experienced comfort[83]. Although there are some studies which used a foggy environment to degrade a driver's situation awareness in a driving simulator experiment[84], it is difficult to control situation awareness in general. The situation awareness global assessment technique (SAGAT[85]) has been used to measure the level of situation awareness. However, it is difficult to use SAGAT to measure dynamic changes in situation awareness. A driver's gaze behaviour can be monitored as a part of situation awareness[86]. Situation awareness is a useful concept but difficult to control or measure precisely, continuously and unobtrusively.

7.3.6 Operating state/mode awareness

The level of a driver's understanding of the state of the system operation/mode may influence takeover performance. Particularly when multiple levels of automated driving exist within the system (e.g. levels 0, 1, 2, 3), an insufficient awareness of the operating mode — called mode confusion — can be an issue[87][83]. Mode confusion can result in a missed or delayed initiation of takeover (both driver-initiated and system initiated) if the driver wrongly believes the system is working at a higher level than is actually engaged[88]. An example use-case is a situation in which the driver believes the system is operating as level 3 and fails to perform the OEDR task when the system is actually operating as level 2. Insufficient operating mode awareness may also lead to automation surprise when the system is actually working without the driver being aware[83].

Operating state/mode awareness may be dependent on an understanding of the driver's role for each level of the system and an understanding the dynamic state/mode of the current system operation. In experiments, instruction of the driver's role for each level and a human machine interface (HMI) displaying the dynamic state/mode of the system operation may control the driver's operating state/mode awareness to some extent[89]. However, it is difficult to control or measure the driver's dynamic operating state/mode awareness. Observation of behaviour in transition may explain some part of the driver's state/mode awareness although it is difficult to separate the effects of state/mode awareness from those effects caused by other factors. Post-drive subjective assessment may be used to assess the operating state/mode awareness of the driver. However, it remains difficult to assess operating state/mode awareness in dynamic shifts between multiple levels.

7.3.7 Attentiveness

The cause of a driver's inattentiveness to the environment can include visual/cognitive loads induced by NDRAs, drowsiness, or mind wandering. Inattentiveness to the environment may result in low situation awareness.

7.3.8 Receptivity

The driver/operator is expected to be receptive to RtIs and evident vehicle system failures as a fallback-ready user with level 3, according to SAE J3016[1]. Receptivity is considered to be a level of readiness/availability rather than a component of it. When extremely drowsy or sleeping, the driver may not notice the RtI signal that determines the threshold of receptivity. When the driver/operator is concentrating on an NDRA, the same situation might occur. The threshold may be determined by the response time instead of the border between the discrete states of receptive and unreceptive. Design of the HMI issuing the RtI and the HMI for other evident vehicle system failures (e.g. intensity of the signal, sensory modality of the stimulus) may influence the threshold of receptivity.

8 System factors that influence takeover performance

8.1 General

It is known that a driver's takeover performance varies with the influences of multiple factors. In experiments, there is a need to appropriately set factors as variables for investigating their effects or better controlling/eliminating their influence. This will allow for designing experiments that are easier to compare with other studies. There are a number of studies seeking improvements of system design and HMIs for better takeover performance. This clause collects information about system factors that may influence driver takeover performance in critical situations. Exploratory studies for HMIs are included in Annex A. This clause does not provide any design principles to restrict or direct the system design. Driver's takeover performance includes time and quality in the driver state transition phase and the post transition control phase (see Clause 10).