Development of a Test Environment for the Evaluation of Human-Technology Interaction in Cockpits of Highly-Automated Vehicles

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Keywords: Automated Driving, Automation, Driver Take-over Task, Driving Simulator, Human-machine Interaction, Human-technology Interaction, Interface Design, Take-over Request, Test Environment, Test Setup.

Abstract: This paper presents a technologically independent framework to describe test environments suitable for the examination of the driver take-over task present in highly-automated vehicles. As part of a structural analysis, typical influencing factors and parameters defining the driver take-over task are discussed. According to literature, existing studies examining the driver take-over task make use of various test environments. However, the comparability of their results is not given without a detailed understanding of these. Hence, based on established literature, a technologically independent framework has been developed which can be used to describe the distinct test environments. It turned out, that the referenced models had to be partially restructured in order to be suitable for the description of such test environments. The focus of the present paper lies on their technical implementation characterized by stimulus materials, which have been holistically examined for the driver take-over task. Since stimulus materials provide the foundation of a specification of test environments, this work presents an initial step towards a test specification aiming on making results obtained from examinations of the driver take-over task comparable.

1 INTRODUCTION

The degree of automation in the field of automotive is steadily increasing. Highly-automated driving is associated with a more comfortable and productive driving experience, allowing drivers and passengers to perform a variety of non-driving related tasks (NDRT).

From the perspective of the commercial vehicle market, high automation degrees have the potential to optimize the utilization by allowing professional drivers to meet their rest times during transit which results in flexibility regarding driving schedules. Hence both, private end-users as well as commercial customers can profit from this trend.

However, as of now, there is no vehicle automation system in high volume production, which is capable of fulfilling all requirements of a L5 system per (SAE International, 2018). Such systems shall have an unlimited operational design domain, meaning that they shall be able to reach a defined target point from a defined starting point anywhere in the world while incorporating redundancy as part of the automation system. As long as systems capable of this are still in development, the driving task as a whole is semi-automated while the level of automation steadily increases with advancing developments in the field of vehicle automation.

Therefore, in the near future, at least a small share of the total distance traveled in a vehicle equipped with an automation system will be driven manually. Typically, this affects the passage of the 'first-mile' and the 'last-mile', respectively the start of the drive (e.g. from parking lot to highway) as well as the end of the drive (e.g. from highway to parking lot).

Hence, in such cases, at minimum one transition from the driver to the automation system (hand-over) and vice-versa (take-over) is required. In order to execute these hand-over and take-over tasks, a human-technology interface, which must provide a safe transition into and out of the automation loop for the driver, is required.

Depending on the share the driver is actively maneuvering the vehicle compared to the automation function having control, different requirements for input and output devices arise. Due to the ongoing advancement of technology, there is a wide variety of solutions available, from traditional cockpit designs

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with head-up displays up to advanced technologies like, among others, e.g. wind-shield displays and augmented reality devices.

In order to implement these technologies into automotive cockpits, they have to be assessed and tested for their suitability. This process requires extensive testing and evaluation, whereas at the same time, the solution space for a cockpit design is increasing significantly.

2 RELATED WORK

2.1 Description of Driving Tasks

Hierarchy of the Driving Task. The hierarchy of the driving task gives a subdivision into the execution of primary, secondary and tertiary tasks based on their contextual proximity to and relevance for the fulfillment of the actual transport task (Bubb et al., 2015; Winner et al., 2015).

The underlying human performance when executing such tasks can be described based on the skill-, rule- and knowledge-based behavior (Rasmussen, 1983) whereas the driving task itself can be categorized into a navigation-, guidance- and stabilization task (Donges, 1982).

These models can be linked to each other content-wise in order to describe the driver's task execution during driving (Winner et al., 2015).

Non-driving Related Tasks. The categorization of the driver's tasks refers to the content-related proximity of the respective tasks to the actual driving task, whereas the primary tasks are closest to the actual driving task in terms of content.

One of the main benefits of highly-automated driving is the potential of the driver focusing on non-driving related (cf. tertiary) tasks while the vehicle is in motion (Naujoks et al., 2017). Hence, automation functions must support a fast and safe transition from the execution of those non-driving related, tertiary tasks to the execution of primary (Othersen, 2016) and secondary tasks, as illustrated in Figure 1.

This paper focuses on the examination of the driver take-over task representing the responsibility shift between the automation system and the human driver.

2.2 Driver Take-over Task

Definition. The driver shifting from an 'out-of-the-loop'-state, often being engaged in tertiary tasks, to having manual control over the vehicle is commonly referred to as the driver take-over task. It is triggered through a driver take-over request (TOR) when initiated by the automation system.

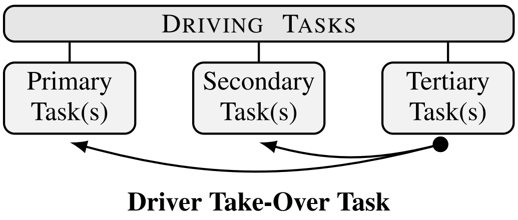

Figure 1: Illustration of the driver take-over task with respect to the hierarchy of the driving task following on from (Bubb et al., 2015; Winner et al., 2015).

The driver take-over task represents the responsibility shift from the automation system to the driver being handled through a human-technology interface.

Defining Parameters. Based on (Eriksson and Stanton, 2017), the driver take-over task can be described by two distinct time intervals: the take-over request lead time TOR_{lt}, giving the time interval remaining until the take-over has to be performed, as well as the take-over reaction time TO_{rt}, the actual time span of the take-over task itself. The examination of (Eriksson and Stanton, 2017) shows that TOR_{lt} and TO_{rt} positively correlate.

Influencing Factors. The completion of the driver take-over task takes significantly longer if the driver has to return to the driving task from being '*out-of-the-loop*' (Merat et al., 2014). Hence, (Banks and Stanton, 2016) suggest to keep the driver engaged in secondary tasks, making the driver an 'active supervisor' of the automation system.

(Wu et al., 2020) indicate, that although the driving duration has a significant effect on the drowsiness level, it has no effect on the take-over performance. However, they have shown that the take-over performance is reduced with increasing *drowsiness*.

Another factor when dealing with automation systems is *mode awareness*, meaning that the driver must be aware which portions of the system are presently automated and which have to be manually controlled. If this is not clear to the driver, this is called *mode confusion*, which is subject to ongoing research regarding automotive interface design (Neuhuber et al., 2020; Pretto et al., 2020).

Furthermore, the behavior of drivers is influenced by their subjective interpretation of the functionalities implemented in the automation function as well as their characteristics, commonly referred to as the driver's *mental model*.

(Neuhuber et al., 2020) indicate a correlation between age and mode confusion, mental models as well as general *difficulties with interaction* with automation systems. Hence, they conclude that the *age* of the driver has a significant influence on the way driver assistance systems are used and that state-of-the-art systems may not be easily used by all groups of drivers.

(Bundesanstalt für Straßenwesen, 2012) lists personal characteristics, which have an influence on driving behavior with the focus on young drivers. However, the categorization can be transferred to all age groups in order to give a qualitative, extensive impression of personal factors which have to be considered when evaluating test environments for highly-automated driving.

Table 1 lists personal factors which have an influence on driving behavior based on (Bundesanstalt für Straßenwesen, 2012). Corresponding to (Bundesanstalt für Straßenwesen, 2012), the listed personal factors are structured into stable and variable characteristics. Stable characteristics contain, among others, sociodemographic aspects, cognitive skills, experience as well as personal characteristics and are not changed frequently.

Contrary to this, variable characteristics, such as fitness to drive, and the current emotional state are subject to a frequent change, which may happen even multiple times per day.

Take-over Times. (Eriksson et al., 2017) compared driver hand-overs *to* and driver take-overs *from* the automation system in vehicles on public roads to driving simulators. They found that the transitions between the driver and the automation system happened generally faster when driving on public roads compared to simulated environments.

Furthermore, (Eriksson and Stanton, 2017) have compared various publications examining the take-over task. Their results show, that the average time needed for a successful take-over request differs in literature. Therefore, making a generic statement about ’typical’ take-over times is difficult based on the available studies.

Comparability of Test Environments. Besides the potential differences in research methods and designs used in the studies, as referenced by (Eriksson and Stanton, 2017), the respective test environment itself as well as their technical implementation may have an influence on the performance of the test person during task execution.

In order to substantiate this hypothesis, the influences on the driver take-over task examined in distinct test environments by different test persons and their effects must be understood in detail to be able to compare studies being performed in varying test environments and explain potential deviations.

Table 1: Personal factors influencing driver behavior (Bundesanstalt für Straßenwesen, 2012).

Personal Factors
Stable Characteristics
Sociodemographic aspects • Age • Gender
Socioeconomic status
Mobility-related attributes • Driving suitability • Driving competence
Cognitive skills • Perception of risk / danger • Concentration and attention • Assessment of own abilities
Schemes
Experience • Mileage • Level of practice • Frequency of driving
Motives, attitudes and expectations
Personal characteristics
Diseases
Variable Characteristics
Fitness to drive
Information processing (e.g. attention control)
Emotions and sensitivities
Diseases
Subjective safety
Subjective task difficulty

This whitespot gives the motivation of a detailed examination of the comparability of test environments used for human-centered studies in the field of automotive cockpit design.

Hence, this paper aims on presenting an approach to a framework providing a guideline to analytically describe a test environment for highly-automated driving along with typical personal influence factors on the respective test persons.

2.3 Test Environments for the Driver Take-over Task

2.3.1 State-of-the-Art

Table 2 shows a categorization of test environments being used to examine driver behavior and human performance from a vehicle driving on public roads ① to laboratory setups ② - ⑧. The test environments have been exemplary arranged based on available stimulus materials.

Immersion & Presence. Depending on the effort put into building up a test environment, different levels of *presence* perceived by the test person can be achieved, which is especially important in laboratory test environments such as ② - ⑧.

Immersion, as a prerequisite of presence (Schwind et al., 2019; Witmer and Singer, 1998), can be reached by the artificial environment matching the user's expectations, being influenced by the user's actions as well as being consistent with regard to its conventions (McMahan, 2003). Hence, stimulus material is an integral aspect for immersion.

Typically, test setups used in literature consist of a narrowed down version of a vehicle cockpit, at least incorporating gas- and brake pedals as well as a steering wheel. The implementation efforts being invested in these depend on the respective research questions being examined and vary widely (cf. Table 2).

Therefore, due to their conceptual differences, results obtained from studies performed in varying test environments can only be compared very selectively and if the test environment, test design and test method has been described in detail.

However, as soon as a study is performed in a laboratory test environment, such as ② - ⑧, the influence of the perceived *presence* of the test person on the result of the examination has to be considered.

2.3.2 Analytical Description

In order to create a common baseline supporting the comparison of results obtained with differentiating test environments, they have to be described holistically on a generic level.

The established 'framework for analyzing the effects of tasks' of (Hackman, 1969) has been chosen as the foundation for this analysis because of its strong relation to stimulus material.

Figure 2 shows an illustration of a generic test environment suitable for an examination of the driver take-over task based on (Hackman, 1969) and is discussed in the following.

Table 2: Test environments being used to examine driver behavior and human performance.

Test Environments		
Exemplary arranged in descending order based on available stimulus materials		
	Description	**Exemplary Implementation**
①	Vehicle on public roads / test track	(Banks et al., 2018; Eriksson et al., 2017)
②	Dynamic driving simulator with screen projection (VR CAVE)	(Schömig et al., 2015; Jamson et al., 2013)
③	Dynamic driving simulator with VR headset	(Hartfiel et al., 2019)
④	Static vehicle with screen simulation	(Petermeijer et al., 2017; Larsson et al., 2015)
⑤	Static simulation with screen projection (VR CAVE)	(Köhn et al., 2019)
⑥	Static simulation with multiple displays	(Li et al., 2019)
⑦	Static simulation with VR headset	(Walch et al., 2017)
⑧	Static screen simulation with minimal input device set	(Capallera et al., 2019)

The *objective task input* is characterized by *stimulus materials*, *instructions about operations* as well as *instructions about goals*. It is subjectively redefined by the test person resulting in the *redefined task input*, whereas this redefinition is influenced by *personal factors* (cf. Table 1).

Following (Hackman, 1969), based on the redefined task input, the test person formulates *hypotheses* on how to approach the given task best in order to achieve maximum success. The hypothetical actions required are executed in the *process* step and result in a *trial outcome*. The *process outcome links* give a causal link between performed actions and outcomes.

The *evaluation* of the performed process can either happen on *system* or *personal* side. If the preceding process execution did not lead to a satisfying outcome, new hypotheses are formed and another iteration is carried out in order to receive a new trial outcome which can be evaluated.

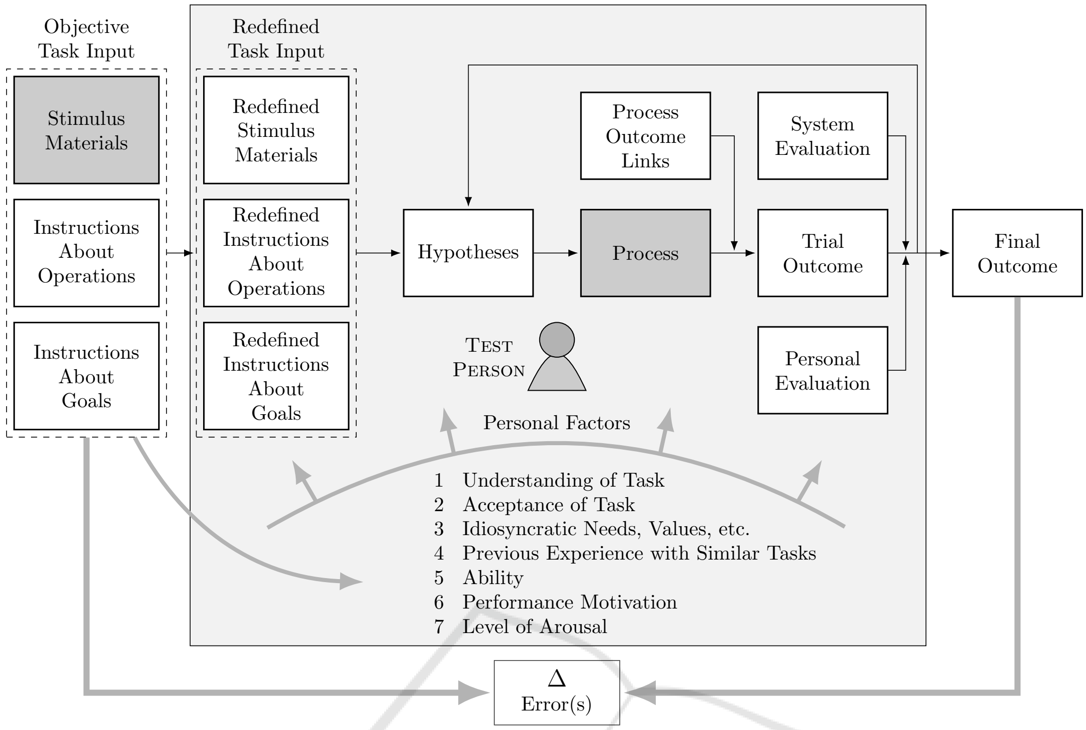

Figure 2: Illustration of a generic test environment suitable for an examination of the driver take-over task based on (Hackman, 1969).

If the evaluation of the trial outcome turns out positive, the result of the last performed process gives the *final outcome*.

The objective task input as well as the final outcome are factors extrinsically defined or evaluated by third parties such as the research team.

The potential difference between the objective task input and the final outcome can be assessed and connected to errors of the test person or systematic *errors* of the technological implementation of the test environment itself and represents the individual performance of each test person.

3 RESEARCH QUESTION, DESIGN AND METHOD

As discussed in Section 2.2, (Eriksson and Stanton, 2017) reference various studies examining the driver take-over task. However, comparing the results of these studies is difficult due to the varying test environments, -methods and -designs being used.

The first step towards a qualitative comparability of these studies is the understanding of the distinct characteristics of the used test environments. Hence, a generic, common basis for a specification of these is required.

3.1 Research Question

An essential characteristic of the common basis for such test environments is the technical implementation required to execute a driver take-over task. This leads to the following research question:

Which stimulus materials are required for the execution of the driver take-over task?

3.2 Research Design

The research question is answered by deriving the technical implementation for a test environment suitable for the examination of the driver take-over task from its structured analytical description.

3.3 Research Method

Established models have been applied to analyze typical test environments for highly-automated driving used for the examination of the driver take-over task.

Based on this, the intention was to be able to holistically describe the driver take-over task considering the respective test environment the task is performed in.

4 RESEARCH RESULTS

As part of the analysis, the hierarchy of the driving task (Winner et al., 2015; Bubb et al., 2015) as well as the framework of (Hackman, 1969) (cf. Figure 2) have been merged into a common context, shown in Figure 3.

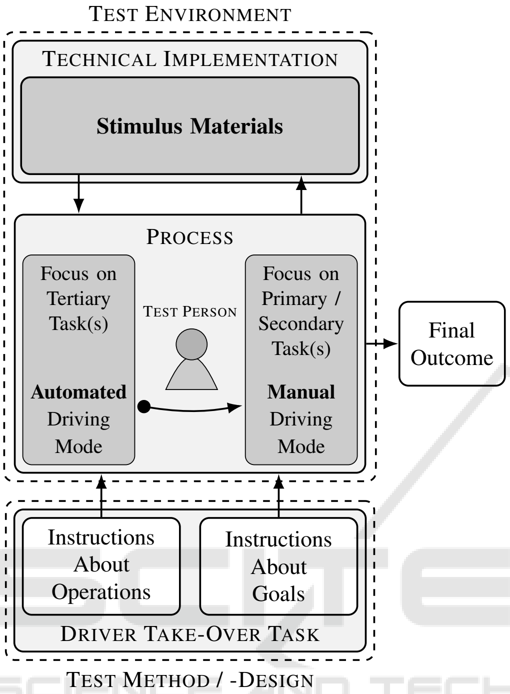

Figure 3: Illustration of a test environment suitable for the examination of the driver take-over task following on from (Hackman, 1969; Winner et al., 2015; Bubb et al., 2015).

As shown in Figure 3, the driver take-over task is performed by a test person inside a test environment as part of the process step (cf. Figure 2). It is characterized by a transition of responsibilities when shifting from the automated to the manual driving mode. The test person's focus typically lies on tertiary tasks during the automated driving mode whereas a fast transition to primary and secondary tasks has to be conducted during the driver take-over task, as already indicated in Figure 1.

Contrary to (Hackman, 1969), who aggregates stimulus materials, instructions about operations and instructions about goals as the 'objective task input' (cf. Figure 2), in the context of a test environment suitable for the examination of the driver take-over task, these can be separated into two distinctive components.

As illustrated in Figure 3, a test environment can be described through its technical implementation as well as the underlying process to be executed. The process is specified by the stimulus materials, the instructions about operations and the instructions about goals which are communicated to the test person. The instructions about operations and the instructions about goals depend on the test method and -design and thus are closely related to the research question in scope of the respective examination.

As shown in Figure 3, the technical implementation must provide stimulus materials allowing an interaction of the test person during the process execution (cf. Figure 2).

Moreover, the stimulus materials serve as an input for the evaluation of the quality of the trial outcome in order for the test person to accept a trial outcome as the final outcome.

Stimulus Materials. The *task qua task* approach outlined by (Hackman, 1969; McGrath and Altman, 1966) provides a suitable analytical foundation for the specification of a technical system implementation of a test environment due to its close relationship to actual physical signals (Hackman, 1969).

Hence, it has been chosen to describe the stimulus materials being part of the technical implementation required to perform the driver take-over task in a test environment.

The stimulus materials listed in Table 3 are structured into categories referring to the ego vehicle, the static environment, the dynamic environment, the drivable space, the traffic as well as the weather at the time the driver take-over request is initiated.

As illustrated in Figure 3, a subset of stimulus materials, typically related to the ego vehicle, are subject to an active interaction by the test person as part of the process execution (cf. Figure 2-3) during the driver take-over task.

Table 4 gives an overview about these and lists the respective processes on a high level.

5 CRITICAL ANALYSIS

This work pursues the idea of creating a common basis for the specification of test environments for automotive cockpit designs in highly-automated vehicles.

The results aim to be applicable to a wide variety of driving tasks and test environments. The driver take-over task has been exemplary selected as a representative task being present in highly-automated driving due to its safety relevance and complexity. In order to get confidence in the generic suitability of this approach, additional work tasks must be described according to the introduced framework.

Table 3: Stimulus materials for a technical implementation of a test environment suitable for the examination of the driver take-over task.

Ego vehicle — *Vehicle the test person is located in*		
Intended destination	Waypoint(s)	For each: • Latitude / longitude, alternatively: • Relative position to the next waypoint
Planned path		
Vehicle dynamics	Velocity (x, y, z)	• Velocity in [x- / y- / z-] directions
	Acceleration (x, y, z)	• Acceleration in [x- / y- / z-] directions
	Vehicle speed	• Vehicle speed signal
	Heading	• [Heading / steering / steering wheel] angle
	Dynamic behavior	• Articulation point(s) • Physically possible max. velocity and accelerations • Slip
Location	Position	• Latitude / longitude, alternatively: • Relative position with regard to the road
Geometry	Type	• [Car / van / pickup truck / truck / bus / tractor / other]
	Size	• Length / width / height
State	Status	• System 'health', automation system state, active gear, lights, etc.
	Errors	• System faults
Static environment		
Static obstacles	Position	• Latitude / longitude, alternatively: • Relative position with regard to the road
	Type	• [Road boundary / construction site] • [Road user in standstill / lost cargo / other]
	Size	• Length / width / height
	Passability	• Passability signal
Dynamic environment		
Other road users	• Vehicle dynamics • Geometry • Position	• *See 'Ego vehicle' section*
Non-road users		
Drivable space		
Drivable space	Road material	• [Asphalt / gravel / sand / dirt / ice / snow], opt. surface condition
	Road information	• Curvature / road boundary position / no. of lanes / lane markings
Traffic		
Traffic	Traffic rules	• Local traffic rules, e.g. [left-hand / right-hand] traffic
	Traffic characteristics	• e.g. Traffic [flow / density / jam], [maximum / mean] speed
Weather		
Weather	Precipitation	• [Rain / ice pellets / snow]
	Light	• [Dawn / day / twilight / night / direct sunlight / clouds / fog]
	Meteorological data	• Temperature / humidity / etc.
Visual range	Visual range	• Resulting from e.g. light, precipitation, meteorological data

Table 4: Stimulus materials being actively influenced by the test person as part of the process execution (cf. Figure 2-3) during the driver take-over task.

Process (cf. Figure 2)		**Stimulus Material**
Control the ego velocity	Control the gas pedal	• Acceleration
	Control the brake pedal	• (Negative) Acceleration
Control the ego heading	Control the steering wheel angle	• Heading
Control the signaling equipment	Control the indicator(s)	• Lights
End the automation	Confirm the take-over	• Automation system state

Furthermore, the amount of potential use-cases, scenarios, environmental conditions and personal factors influencing the driver take-over task lead to a large number of different variations. Hence, the presented tables, figures, lists and examples do not claim to be exhaustive.

However, the presented approach can support the comparability of studies by providing an initial but important step towards a documentation guideline for studies investigating human performance in driver take-over situations.

The presented approach was developed through analytical research. To prove its suitability, it should be applied to further test environments and studies examining the driver take-over task.

The content of this paper covers the description of the technical implementation of a test environment. The instructions about operations and the instructions about goals, which depend on the respective test method and -design, closely related to the research question in scope, have to be assessed separately.

6 CONCLUSIONS

6.1 Summary

In order to be able to compare studies examining the driver take-over task using differentiating test setups, a common descriptive basis is required to understand their coinciding results and potential deviations. Therefore, this paper presents a technologically independent description of test environments in the field of highly-automated driving based on established research models and literature. It can be used likewise for the analysis of existing test environments as well as for the definition of requirements for new test environments to be build up.

The analysis has shown that a test environment is influenced by two major components: the technical implementation as well as the test method and -design (cf. Figure 3). The test environment contains aspects being subjectively influenced by the test person, such as the execution process of the task itself (cf. Figure 2). The technical implementation consists of stimulus materials which represent interaction with the process.

The test environment can be used to examine the research question in scope along with the test method and -design. These are derived based on the research question and contain instructions about operations as well as instructions about goals (cf. Figure 2-3, (Hackman, 1969)).

The presented analysis focused on the identification of necessary requirements for the technical implementation of a test environment suitable for examining the driver take-over task. The specification for stimulus materials for such test environments is given in Table 3, while those being actively influenced by the test person during the driver take-over task are highlighted in Table 4 respectively.

As Table 3 shows, various stimulus materials must be made available to the test person due to their influence on the situation interpretation and hypothesis selection of the driver when performing the take-over task (cf. Figure 2-3).

6.2 Discussion

Although the structural analysis presented in this paper builds on (Hackman, 1969), it turned out to be more suitable to describe test environments by separating stimulus materials, instructions about operations and instructions about goals into a component with technical relation (technical implementation) as well as another component with relation to the test method and -design used for the examination. Hence, the objective task input, as it was introduced by (Hackman, 1969), can be subdivided further for this application.

However, the redefined task input, as it is described by (Hackman, 1969), is part of the test environment since it is influenced by the test person's personal factors which corresponds to (Hackman, 1969) and gives an input to the process (cf. Figure 2).

The presented approach is meant to create awareness for the multitude of factors and stimulus materials, which have to be considered when conducting an examination related to the driver take-over task. This is especially relevant for studies being conducted in laboratory test environments (cf. Table 2). However, the discussed aspects similarly apply to other driving tasks.

To achieve comparability of the available studies examining the driver take-over task, researchers should describe the stimulus materials provided to the test person in the respective studies in detail in order to support a comprehensive interpretation of their results. Therefore, especially when publishing results obtained from using laboratory test environments, it is recommended not only to describe the technical setup itself, respectively *how* certain stimuli have been provided, but additionally provide details on *why* it has been decided to tailor certain stimuli compared to driving in a vehicle on public roads, if applicable.

Hence, this sets new demands on the documentation of studies conducted in this field.

6.3 Outlook

In a subsequent analysis, instructions about operations and instructions about goals provided to the test person as part of the test method and -design have to be examined in order to holistically understand potential influencing factors on the driver take-over task.

The differences between the objective task input and the final outcome, as introduced in Figure 2 as errors, can be categorized based on human error models available in literature, which supports the understanding of human interaction with automated driving systems. The ability to understand the origin of human errors during the driver take-over task is essential during the design phase of human-machine interfaces for the driver take-over task.

Furthermore, the proposed models should be implemented in existing studies in order to prove their suitability. Following on from this, a generic guideline can be developed, which supports the planning, execution and evaluation phase of studies.

To continue working on this aspect, a test specification containing a common set of criteria, descriptive categories and boundary conditions can be developed. This can then be published as an appendix to the respective studies in order to facilitate their comparability leading to more resilient research results.

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