Development of a human driver model during highly automated driving for the ASIL controllability classification

A novel approach on modeling takeover scenarios for highly automated driving

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***Abstract* – The number of cars on the road equipped with advanced driver assistance systems (ADAS) such as adaptive cruise control (ACC) or autonomous emergency breaking (AEB) is steadily increasing. To determine the functional safety requirements for ADAS the development-process is defined by the ISO 26262. Therefore, this standard classifies the systems failure modes depending on severity, controllability and exposure. While active, these systems currently require the driver to supervise the system at all times and to be able to react quickly on system failure by holding the steering wheel constantly. Future ADAS will allow the driver to complete non-driving related task such as reading or playing games. In this case, the ISO 26262 currently fails at defining a plausible controllability-factor since the driver is not holding the steering wheel or supervising the system. Therefore, another way of defining a controllability factor during "hands-off" driving is needed. In this paper, we introduce a novel way of defining the controllability factor for the ASIL classification based on the analysis of human driver models and several studies on takeover-times during highly automated driving.**

Keywords – functional safety, ISO 26262, ASIL, controllability, highly automated driving, advanced driver assistance system, hands-off, non-driving related task, situation awareness, mode awareness, responsiveness, takeover

I. Introduction

The technical standard IEC/EN 61508 describes the safety requirements for electric, electronic and programmable systems in general. Based on this standard the ISO 26262 standard is derived which describes the safety requirements for electric and electronic devices in road legal vehicles. Part three of the ISO 26262 describes the hazard and risk analysis in case of systems malfunctioning during all foreseeable operating conditions. For this analysis every safety risk is assessed based on three factors: severity, exposure and controllability. Based on these factors an automotive safety integrity level (ASIL) is derived, which defines the safety requirements to reduce those risks to acceptable levels. The severity factor describes the potential hazard to human beings. The exposure describes the likelihood of the scneario to occur during operating times and the controllability how likely it is that the average driver can handle this scenario. The severity and controllability factors are categorized from 0 to 3 and the exposure factor from 0 to 4. Table 1 shows the resulting ASIL-Classification from which the safety requirements for the ADAS are derived. The ASIL-A classification results in the lowest and the ASIL-D classification in the highest safety requirements. The ASIL-Classification also allows a decomposition of safety-requirements. This means that an ASIL-D classified system can be accomplished by combining two redundant ASIL-B systems or by combining an ASIL-A and an ASIL-D classified system. To reduce costs automotive-manufactures try to avoid high ASIL-Classification since higher classifications usually increase the need for redundant systems. [1]

TABLE I. ASIL Classification [1]

Severity	**Exposure**	**Controllability**		
	[time in use]	Likelihood controllable by avg.		
		C1 ≥ 99 %	**C2 ≥ 90 %**	**C3 < 90 %**
S1 Light injuries	**E1** < 0.1 %	QM	QM	QM
	E2 < 1 %	QM	QM	QM
	E3 < 1 % - 10 %	QM	QM	A
	E4 > 10 %	QM	A	B
S2 Server injuries, not life threating	**E1**	QM	QM	QM
	E2	QM	QM	A
	E3	QM	A	B
	E4	A	B	C
S3 Life threating injuries	**E1**	QM	QM	A
	E2	QM	A	B
	E3	A	B	C
	E4	B	C	D

As shown in Table I the highest ASIL-Classification D can only be achieved if less than 90 % of the average drivers are able to handle the malfunction. This shows the importance of the controllability factor and the need to analyze controllability from a percentile point of view. For this classification, the driver always supervises or controls the vehicle. This means that the driver is fully aware of the situation he is in and the mode of the ADAS. In the BASt classification [2] such a system would represent a “partly automated system”. Future ADAS will allow the driver to accomplish NRDTs and do not require the driver to supervise the system while it is active. While these systems are active the driver will still be needed to takeover control occasionally since the ADAS is not able to handle every situation. Such a system is defined by the BASt as a “highly automated system" system [2]. In case of a takeover the driver will likely not have a full understanding of the situation he is in or the mode of the ADAS. Therefore, a detailed analysis of the driver’s situation awareness during highly automated drive is needed to understand the driver's ability to control the malfunction. In addition, the driver will likely not be able to take over control instantly but rather after a short period of time in which the driver stops the non-driving related task (NDRT), gains situation awareness and then takes over the control of the car. Logically from this follows that the ADAS has to alert the driver about an upcoming malfunction before the system boundary is reached. In case of an unpredicted malfunction the ADAS has to be able to safely control the car until the driver takes over. For this work, we define these time-slots as time-to-event (TTE). Therefore, higher TTE should result in a higher controllability since the driver has more time to react and takeover. But to determine the controllability factor we need the percentiles of drivers who manage to control the malfunction depending on a given scenario and TTE. To tackle this problem a quantitative analysis of the human driver during takeover scenarios is needed.

II. Quantitative model

To understand the human takeover process and the relationship between controllability and the terms situation awareness, mode awareness as well as responsiveness better, it seems reasonable to develop a system model in this regard. This model should be able to represent the driver and the vechicle druing highly automated drive and the take over process. Since the driver does not have to monitor the traffic situation permanently he is free to deal with a NDRT. Therefore, in addition to the "driver" and the "vehicle", the "non driving related task" must be included in the model as a system element. Since it cannot be assumed that the distracted driver will recognize when his intervention in the highly-automated drive is necessary, a takeover request must be provided. This should also be considered in the system model.

Endsley's decision-making process [3] and Abendroth's driver-vehicle-environment system model [4] are the starting point for our system model. Endsley [3] takes the situation awareness during a decision-making process into account. She defines 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" [5]. Endsley [3] [6] opine that the three levels of perception, comprehension and projection must be passed through to achieve situation awareness. A higher level can only be started if lower one is finished. In her approach [3] a human being decides based on his situation awareness and acts accordingly. Mode awareness is a part of the situation awareness and should be respected if needed [7]. According to Othersen [7], the same process as Endsley's definition of situation awareness is important: perception, comprehension and projection. The difference between situation and mode awareness is only the scope of information: while situation awareness includes the status of the whole environment, mode awareness deals exclusively with the system-relevant information.

In Abendroth's system model [4] the system elements "driver" and "vehicle" are surrounded by the environment. The system has several input, output and disturbance variables. The "driver" controls the "vehicle" via the control elements and receives information from the "vehicle" via an interface. Abendroth [4] specifies the "driver" by his individual characteristics and his information process, whose processing steps needs attention resources. The driver takes the information of his environment via the visual, acoustic, haptic and vestibular sense and saves them in the sensoric memory. Afterwards, the information is processed further. Following Rasmussen's human performance model [8] the driver behaves, depending on the type of task, skill-based, rule-based or knowledge-based. During this process, the driver reverts to his working memory. The result is an action selection, which is executed by the hand-arm-system and the foot-leg system [4].

Abendroth describes the interplay between driver and vehicle during a manual trip. The model is less suitable for the highly-automated driving. For this reason, we need to develop an own system model containing the "driver", the "vehicle" and the "non-driving related task" as system elements. Figure 1 visualizes the system element "driver". We follow Abendroth, but make some adjustments due to the highly-automated driving.

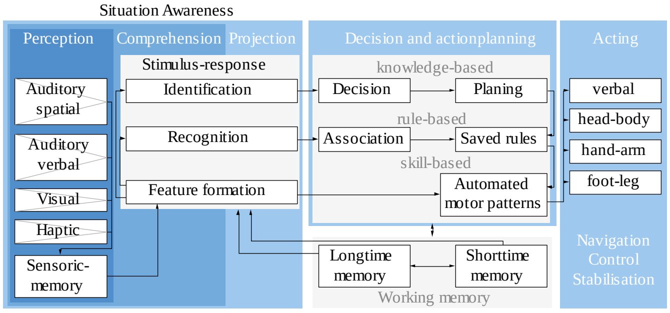

Fig. 1. System element "driver"

The changes affect the stimulus reception by the receptors and the information delivery. The presentation of the stimulus reception by the senses are modeled on the multiple resources theory [9]. Following Wickens’ approach, the acoustic and visual stimulus reception are independent of each other, so that no interferences arise. As already criticized by Damböck [10], Wickens considers only the sensory channels mentioned above. In addition to the acoustic and visual sense, the human also uses the haptic and the vestibular sense for managing the driving task

[11]. In case of a system malfunction the takeover request may be an acoustic, a visual or a haptic stimulus. These are included in Figure 1. Following Wickens [9] we differ the acoustic sensory channel between spatial and verbal. The independence between the different stimulus receptions is represented by the four different input blocks. The triangles inside the block symbolize a filter: the senses perceive only the stimuli which are anatomically perceptible.
Our motivation to adjust the information delivery process can be explained as follows. Wickens [9] distinguishes in the multiple resources theory between verbal and motoric responses. According to Abendroth, an additional differentiation of the motoric action between the hand-arm-system and the foot-leg-system seems reasonable. In addition, we consider the head-body-system, which a human e.g. needs in case of a shoulder check or lifting the head after being lowered due to a NDRT. Even if the verbal response cannot influence the vehicle guidance, it is relevant for NDRTs during highly-automated driving. Therefore, Figure 1 considers this. Similar to the two different responses (verbal, motor) in the multiple resources theory, a human can perform the four types of action relatively independently of another. Following Donges [12], the driving task can be categorized according to stabilization, control and navigation. This aspect is also taken into account. Endsley's decision-making process is also arranged in shades of blue. In addition to the "driver", our system model (Figure 2) contains the "NDRT and the "vehicle". Latter is divided into "advanced driver assistance system" (ADAS), the "switch" (steering wheel, pedals or other control elements) and the rest of the vehicle (e.g., display or the driving dynamics). As represented by the switching element, the driver can determine whether he controls the dynamics of the vehicle or whether the ADAS is in control.

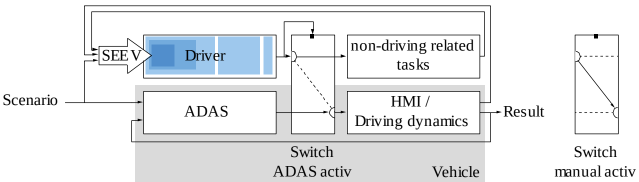

Fig. 2. System model

The system elements are surrounded by an environment in which the driver or the ADAS control the car. Both receive via their perception a situation input from the environment. In addition, both receive a feedback from the current dynamics of the vehicle, which also represents the result of the control loop. Overall the driver obtains three inputs: the situation input, the mode input and the input from the NDRT. In this system model a takeover request is transmitted via the mode input. During a takeover the driver's inputs compete for the resource capacities, since all the information needs to be acquired, processed and delivered. With the described adjustments, this resource utilization is comparable to the multiple resources theory. Following the SEEV model [13] the probability that a stimulus is perceived by a human can also be predicted by the salience, the effort, the expectation and the value. This context is represented by the "SEEV" arrow in Figure 2.

With this model the driver's responsiveness, situation awareness and mode awareness can be represented qualitatively. In case of a takeover request, the responsiveness depends on the situation awareness, its component mode awareness, the ability to make the right decision and the motoric responsiveness. If the driver has the ability to react appropriately in the available time and if the technical possibilities of the vehicle are accordingly, the situation can be mastered. The argument presented above shows that the qualitative system model is not sufficient to make a reliable prediction of the controllability for a given scenario. Such a prediction may only be made if both, the time intervals of the processes and a representation of the temporal sequence are available. Based on the system model, we derive both requirements in the next chapters.

III. Analysis of Several Studies

To fully understand the human takeover process we look at different studies, which investigate takeovers during highly automated driving. Only those studies are considered, in which the driver performs a NDRT and in which there is no need for the driver to switch off the system before the takeover but instead is able to override the system at any time. In addition, the studies must contain a definition of the measured reaction times. We analyze the following eight studies:

1) Damböck et al. (2012) [14]
2) Gold et al. (2013) [15]
3) Petermann-Stock et al. (2013) [16]
4) Lorenz et al. (2014) [17]
5) Radlmayr et al. (2014) [18]
6) Gold et al. (2015) [19]
7) Petermann-Stock et al. (2015) [20]
8) Zeeb et al. (2015) [21]

We differentiate the reaction times that are published in the studies in the orientation-time (OT), the ready-for-action-time (RAT), the action-execution-time (AET) and the vehicle-stabilization-time (VST). The measurement of the four different reaction times starts with the takeover request. The orientation-time ends by the glance aversion from the NDRT or by the fixation of traffic-relevant objects. The ready-for-action-time ends when the driver touches the steering wheel or places a foot on the pedal. The action-execution-time ends by the beginning of the control action (steering or pressing the pedal). The vehicle-stabilization-time always describes the elapsed time from the takeover request until the actual state matches the desired state.

The analysis of the studies shows that there are different influencing factors which have impact on the takeover during highly automated driving. These factors are categorized into four groups: influence on driver, situation input, mode input or NDRT. Table II shows which areas of the qualitative model are affected by those factors.

Based on the studies done by Petermann-Stock et al. (2013) [16] and (2015) [20] it is possible to identify the effects of age

on the cognitive and motoric processes. Younger people show a faster motoric action, therefore they are able to move the arms and feet faster to the steering, wheel and pedal (shorter ready-for-action-time). Since older drivers usually have more experience, they are able to decide faster and partly more appropriately.
Petermann-Stock et al. [16] also show that the 2nd takeover improves compared to the 1st takeover. This can be explained by learning effects, which leads to the conclusion that the driver's experiences and skills also influence the quality and time of takeovers. In their study Zeeb et al. [21] relate the quality and time of the takeover to the gaze behavior: Depending on the gaze behavior they classify the drivers into groups: "high-risk", "middle-risk" and "low-risk". Zeeb et al. do not find a relation between gaze behavior and orientation-time or ready-for-action-time. However, subjects of the low-risk group have a longer action-execution-time and can rarely avoid a collision. Therefore, gaze behavior can be used as an indicator of the individual ability to take over the driving task again.

TABLE II. PLACEMENT OF THE INFLUENCING FACTORS

	Influencing factors	Temporal influence on						
		perception	comprehension	projection	decision	working memory	performance	attention
driver	age		x	x	x		x	
	characteristics	X	x	x	x	x	x	x
	experience					x		
	highly automated driving time							x
situation input	driving task				x		x	
	traffic volume		x	x				
mode input	stimulus	X						
	TTE		x	x				
	support for SA/MA	X	x	x				
NDRT	type	X					x	
	bond	X						
	cognitive load	X	x	x				x

The influencing factors of the situation input are the driving task and the traffic volume.
In their study, Damböck et al. [14] develop three scenarios, which provide different driving tasks to the subjects. These are categorized according to Rasmussen's human performance model and Donges' three-levels hierarchy of the driving task. However, Damböck [10] argues that the analysis of the measured AET times is not useful due to the partial small sample size taken into account. Concrete statements based on these values are therefore, not possible. However, referring to the human performance model and the three-level hierarchy of the driving task we can assume a link between the driving task and the human takeover.
The studies of Radlmayr et al. [18] and Gold et al. [19] show that a higher traffic volume increases the AET but not the RAT. Since higher traffic increases the complexity of the situation it is more difficult for the driver to understand the situation (situation awareness: level 2) and to project the future status of the individual objects (situation awareness: level 3).

The influencing variables of the mode input are the warning modality, the TTE as well as the system-based support of the mode and situation awareness.
In a study Petermann-Stock et al. [20] investigate the relation between the takeover time and different takeover requests. They show that an acoustic warning generates shorter reaction times than a visual warning. Petermann-Stock et al. also investigate the verbal and the haptic modality. The latter can be compared with an acoustic stimulus - but there is a risk of a lack of reaction. The verbal modality is able to inform the driver exactly about the situation and the optical modality is the slowest and may be easily missed.
Damböck et al. [14] and Gold et al. [19] show an influence of the TTE on the takeover. The RAT and AET increase with longer TTE. The driver uses the gained time mainly for comprehension and projection of the situation, which improves the takeover quality. The opposite effect is observed for shorter TTE.
In addition, support for the situation and/or mode awareness may shorten the takeover times. Lorenz et al. [17] investigate the influence of augmented reality (AR). Their results show that a visual driver support via AR shortens the AET and results in a better takeover quality.

The influencing variables of the NDRT are the type, the bond and the cognitive load. In a study from 2013, Petermann-Stock et al. [16] analyze three different quiz forms. The difference is whether the subject has to read the answers or they are being read to him and whether the subject has to answer the questions in written form or verbally. The authors' results show that the AET increases from quiz "low", over "mid" to "high". Since the 70 questions about general knowledge, language as well as spelling and grammar are used equally for all three quiz variants, the cognitive load should be the same in all three variants. Therefore, the cause for the various takeover times must be the information-recording and delivery processes. In this study the AET is longer after doing the visual and motoric NDRT than after the acoustic and verbal one. This effect can be explained by the situation awareness model. The first level of the situation awareness (perception) is already significantly impaired by the visual diversion. Therefore, the achievement of an appropriate situation awareness is more difficult. On the other hand the acoustic NDRT allows a visual monitoring of the situation which results in a higher situation awareness. In addition, Petermann-Stock et al. [16] evaluate the internal incentive to perform the quiz "high" higher than to perform the quiz "low". Therefore, the longer takeover time can also be explained by the higher internal incentive (bond).
Radlmayr et al. [18], however, are able to show that the takeover times for the acoustically, cognitively and verbally demanding n-back Task is nearly as long as the takeover time for the visually, cognitively and motorically distracting Surrogate Reference Task (SuRT). In contrast to the study of

Petermann-Stock et al. the results can be explained by the cognitive load: the driver is able to observe the situation during the n-back task. However, the cognitive load from the NDRT is so demanding that the driver has as little to none situation awareness compared to the driver who is visually distracted by the SuRT. Radlmayr et al. [18] share the same opinion.
Other influencing variables than the ones mentioned above may exist. Vogelpohl [22] suspects an influence of the road curvature, the speed and the kind of the road on the human takeover. Other variables might be the highly automated driving time, the weather and the daytime.

IV. Quantifying Model

As stated above, a situation is controllable if a person has the ability to react adequately in the available time and if the technical capability of the vehicle allows the desired driving task. Since our system model does not include a time aspect we develop a flow chart to represent the chronological order of actions in our system model. The flow chart contains the individual actions as blocks which are necessary for the takeover process. Each action requires a specific time and different paths can be selected to model different takeover situations.
The following chapter describes the development of the flow chart for the takeover process and explains the resulting quantifying model. Afterwards the approach is validated.

A. Flow chart

Based on a flow chart from Damböck [10], our system model (Figure 2) and the identified influencing factors (Table II) we develop a new flow chart which represents the drivers actions during a takeover (Figure 3).
The takeover process during highly automated driving with NDRT happens in four different phases:

- 1st phase - turning-to-the-situation: During the 1st phase, the driver perceives the takeover request by his senses and averts cognitively and, if necessary, visually from the NDRT. Afterwards he is ready to turn to the driving task relevant situation.
- 2nd phase - situation processing: The driver passes through the three levels of situation awareness and chooses an appropriate action.
- 3rd phase - readiness-to-act-action: During this phase, firstly the driver removes the motoric distraction from the NDRT and secondly moves his hands and feet to the appropriate control elements of the vehicle.
- 4th phase - situation action: This phase contains the execution of the selected action. The end of this phase is the achievement of the desired state.

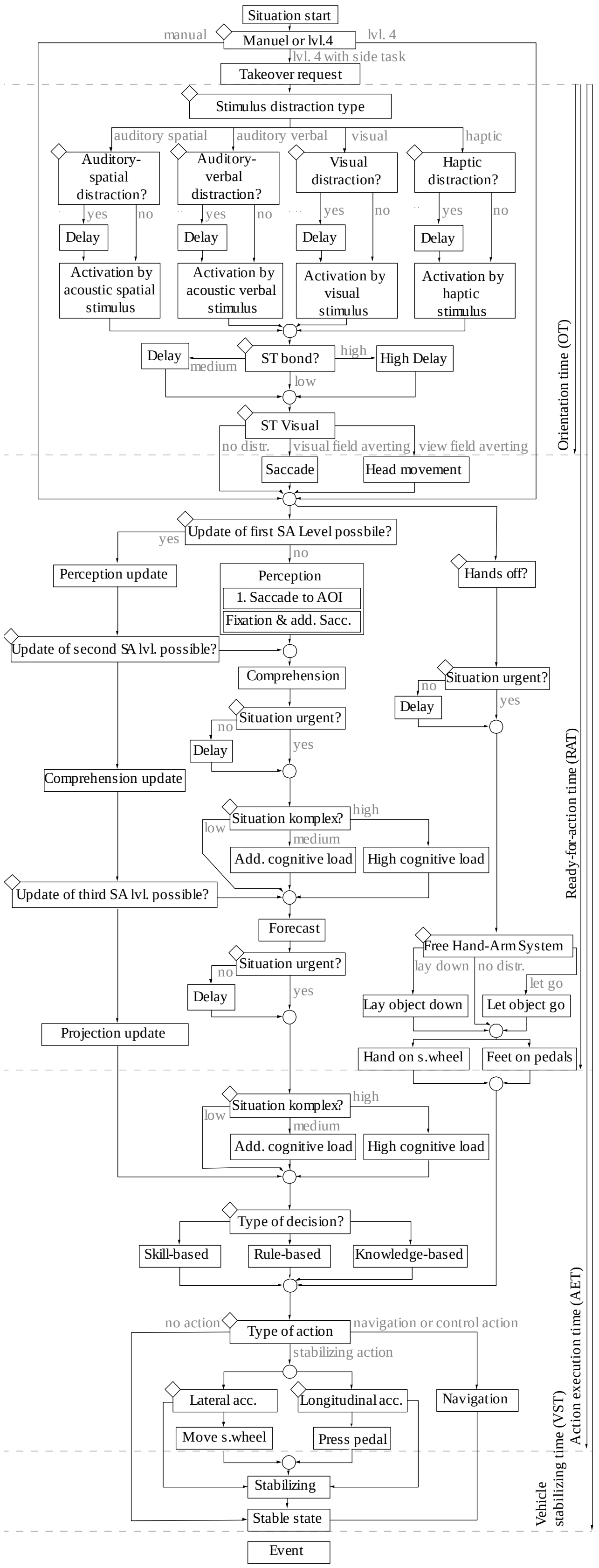

Fig. 3. Flow chart: Qualitative model of the human takeover-process during highly automated drive with NDRT. Diamond block represents a branch in the flow chart.

With reference to Zeeb et al. [21] and the multiple resources theory [9] the driver may start the 2nd and 3rd phase simultaneously after the first phase is finished. The 4th phase starts after both the 2nd and the 3rd phase are finished.

If the driver is driving manually or observing the traffic during highly-automated driving the first phase might be skipped. If the driver is distracted during a highly automated drive a takeover request will ask the driver to take over the control of the car. As presented in the qualitative model, this request may be an auditory-spatial, an auditory-verbal, a visual or a haptic stimulus. Since the corresponding sensoric channel might be occupied by the NDRT interferences arise [9]. These interferences may lead to a delay of perception. In case of a multimodal warning, the stimulus that is received the fastest is decisive for further processing. After the driver perceives the stimulus, he has to avert cognitively from the NDRT. Petermann-Stock et al. [16] introduce the concept of the internal incentive while performing the NDRT. The internal incentive can be categorized as low, medium or high bond. The higher the bond, the more time the driver needs to avert from the task. Then, the visual distraction, which may exist due to the NDRT, can be eliminated. We differentiate between visual field averting and view field averting: in the first case a saccade movement and in the second case a movement of the head-body-system is made.

After the first phase, the situation processing and the readiness-to-act-action start simultaneously. The longer of the two phases determines the beginning of the 4th phase situation action.
During the situation processing, the driver has to gather the situation awareness before he is able to make a decision. The literature and studies we found do not measure the situation awareness considering takeover time and takeover quality at the same time. Therefore, we develop the following theoretical approach. According to Endsley [3] the three levels (perception, comprehension, projection) have to be passed to achieve situation awareness. A higher level can only be started if the lower one is finished. Based on this step-by-step design, we derive the following model: The driver is driving in highly automated mode. The situation changes and the driver is being requested to take control of the car. Before the change, the driver may have knowledge about the situation on the first level (perception) or not. In the first case, he only needs to perceive the changes, which contain one or only a few elements. If so, he is able to update the perception level. In the second case, the driver must perceive all the other elements of the situation in addition to the changes. The same applies to the second (comprehension) and the third (projection) level. If the driver has knowledge at the respective level immediately before the situation changes, he is able to update the corresponding level. Since the three levels are hierarchically depended, the following restriction applies: The update of a level is only possible if the update of the previous level was possible. E. g. the driver has no knowledge at the comprehension level, if he has no knowledge at the perception level. Consequently, it cannot update either the 1st nor the 2nd level.
As shown in Table II, the three levels of situation awareness are dependent on different influencing variables. The type and the size of cognitive load of the NDRT determine whether an update of a situation awareness level is possible or not. In the case of manual driving and a highly automated supervised driving, an attentive driver is assumed. Before the situation changes, he has a complete situation awareness and is able to update all three levels. This is also possible performing a NDRT, which is not visually and not cognitively distracting. According to Rockwell [23], humans gather 90 % of the information by the visual sensory channel. For this reason, we assume that in case of visually distracting NDRTs the driver has no situation awareness. Therefore, an update is not possible at any level. Since the authors are looking at takeover-times this statement represents a conservative assumption to the safe side. Radlmayr et al. [18] show in their study a comparison of the activities SuRT and n-Back. They find that a cognitively demanding task can lead to a similar distraction - and thus to a low situation awareness - as a predominantly visual task. Taking this into account, a driver with a cognitive task does also not have situation awareness. Table III shows the gradation between a NDRT with no cognitive load and a high cognitive load.

TABLE III. MATRIX FOR UPDATING THE SITUATION AWARENESS

Driving mode	**Visually distracted**	**Cognitive load**	**Perception updating**	**Comprehension updating**	**Projection updating**
manual	no	no NDRT	yes	yes	yes
highly automated	no	no NDRT (supervising)	yes	yes	yes
	no	no	yes	yes	yes
	no	low	yes	yes	no
	no	middle	yes	no	no
	no	high	no	no	no

The collection of situation awareness can be supported by the system. According to Endsley's hierarchical structure [3], the following supports are possible:

- support for perception
- support for perception and comprehension
- support for perception, comprehension and projection

An update is possible at the supported level.

The second and third level of the situation awareness are influenced by the complexity, which results from the traffic density and the urgency of the situation. The urgency depends on the TTE. Therefore, the two influences are taken into

account in the comprehension and projection level. In case of a low priority, the driver has more time at the second and third level. Higher complexity requires higher cognitive performance, which results in a higher takeover time.
The driver chooses, based on his situation awareness, an appropriate task. This task can be skill-based, rule-based or knowledge-based.

A readiness-to-act-action depends on the distraction of the hand-arm-system and foot-leg-system and therefore, on the type of NDRT. If the driver's hands hold the steering wheel, this phase does not need be finished, since we assume that the feet are also in the correct position. During hands-off driving, we differentiate whether the driver has to let an object go or lay an object down to remove the distraction of the hand-arm system. Only after the distraction is removed he is able to move his arms and feet to the correct position.

The final phase is the situation action. Depending on the driving task, the driver performs a stabilizing, control or navigation action. So far, we are only looking at a skill-based stabilizing action. In this case the driver presses the pedals for a longitudinal acceleration and turns the steering wheel for a lateral acceleration until the desired state is reached.
In Figure 3 we delineate the OT, RAT, AET and VST according to their definition.

B. Quantifying model

The developed flow chart is the foundation for the quantifying model. The idea of the approach is to sum up each time for each action that is part of the selected path. The result is the total time for the considered takeover situation. The challenge is to find the correct timespans for each action. The literature and the analyzed studies provide mainly mean values and associated standard deviations for the times of the actions. At the same time, the classification of controllability according to ISO 26262 requires the description of percentiles. In order to achieve this, we assume that there is a normal distribution at each action time, which is defined by its mean value and its standard deviation.

By adding the mean values of the l relevant actions $\mu_1, \mu_2 \dots \mu_l$ contained in the flow chart, we obtain the mean value of the considered reaction time:

$$\mu_{reaction\ time} = \mu_1 + \mu_2 + \cdots + \mu_l$$

To obtain the associated standard deviation we follow Bronstein et al. [24] with respect to the linear case of the Gaussian error propagation law:

$$\sigma_{reaction\ time} = \sqrt{{\sigma_1}^2 + {\sigma_2}^2 + \cdots + {\sigma_l}^2}$$

The percentile can be calculated by the resulting normal distribution.

Therefore, our approach requires the specification of a mean value and a standard deviation of each action listed in the flow chart. We determine the times of the motoric actions via Schmidtke [25]. The values for the activation by a stimulus are based on author information with regard to the single reaction times [26] [27]. The remaining values are determined by the subtraction method, which we apply to specific time periods of the analyzed studies.

Using the determined time data, we implement our approach in a tool that calculates the reaction times for different situations, shows their distributions graphically as normal distribution curves (Fig. 4) and determines the controllability of the situation. The user is able to create different scenarios by specifying the influencing variables and selecting which reaction time is relevant for the controllability.

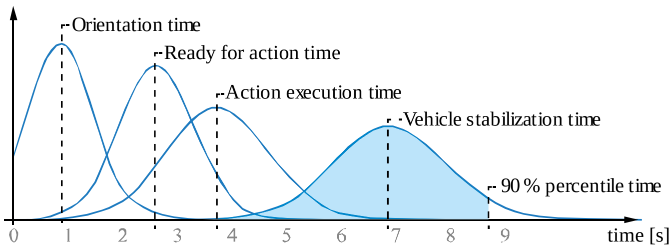

Fig. 4. Reaction times for a given scenario and the corresponding 90th percentile

C. Validation

For the validation of the model, we calculate the reaction times of the analyzed studies except for Petermann-Stock et al. (2013) with the developed tool (Petermann-Stock et al. do not report the exact value of the TTE that is necessary for the calculation of the AET). Afterwards we compare the results with the respective authors' data by creating the difference between both times. The difference δ is defined as follows:

$$\delta = value\ of\ the\ study - calculated\ value\ by\ the\ tool$$

The mean times and the associated standard deviations are considered as values. We determine that a deviation of 0.25 sec between a value specified in the study and the associated value calculated by the tool is tolerable.
Table IV represents the results of this comparison. If differences occur, it is marked red. If differences can be explained, we use yellow instead and matches are marked green. If a value of the study has been used for the determination of the data, we use blue.
Table IV shows that the quantifying model calculates proper takeover times for the most studies.

TABLE IV. VALIDATION

Scenarios of each studies	Orientation time		Ready for action time		Action execution time	
	δ_{MV} [s]	δ_{SD} [s]	δ_{MV} [s]	δ_{SD} [s]	δ_{MV} [s]	δ_{SD} [s]
Damböck et al. (2012)						
no lane marking, TTE = 4 s	0,01	-0,18	-0,06	0,30	0,73	-0,25
no lane marking, TTE = 6 s	-0,05	-0,24	-0,23	0,10	0,26	-0,35
no lane marking, TTE = 8 s	-0,07	-0,24	-0,06	0,19	0,85	0,89
lane narrowing, TTE = 4 s	-0,05	-0,18	-0,02	0,30	-	
lane narrowing, TTE = 6 s	0,04	-0,13	0,01	0,21		
lane narrowing, TTE = 8 s	0,01	-0,18	-0,05	-0,03		
roadway division, TTE = 4 s	-0,07	-0,24	-0,11	0,09		
roadway division, TTE = 6 s	0,03	0,01	-0,10	0,16		
roadway division, TTE = 8 s	-0,02	-0,19	-0,35	0,02		
Gold et al. (2013)						
TTE = 5 s	-0,12	-	0,01	-	-0,02	0,06
TTE = 7 s	-0,01		0,23		0,36	0,51
Lorenz et al. (2014)						
No AR	0,00	-	-0,17	-	-0,10	0,04
AR green	0,03		0,29		-0,14	0,12
AR red	-0,02		0,13		-0,19	-0,02
Radlmayr et al. (2014)						
Situation 1, n-BT	-				-1,06	0,16
Situation 1, SuRT					-1,34	0,30
Situation 2, n-BT					-1,13	-0,35
Situation 2, SuRT					-0,74	-0,01
Situation 3, n-BT					-0,82	-0,07
Situation 3, SuRT					-0,97	0,06
Situation 4, n-BT					-0,65	0,09
Situation 4, SuRT					-0,92	-0,13
Gold et al. (2015)						
0 vehicles per km	-		0,65	0,00	-0,10	0,39
10 vehicles per km			0,56	-0,13	-0,10	0,35
20 vehicles per km			0,72	0,09	-0,10	0,37
Petermann-Stock et al. (2015)						
elderly drivers, haptic stimulus	-0,02	-0,32	-			
elderly drivers, verbal stimulus	-0,04	-0,29				
younger drivers, haptic stimulus	0,19	-0,06				
younger drivers, verbal stimulus	0,10	-0,01				
eld. & young driv., acoustic stimulus	0,03	-				
eld. & young. driv., haptic stimulus	0,02					
eld. & young. driv., visual stimulus	0,14	-0,30				
eld. & young. driv., verbal stimulus	0,00	-				
Zeeb et al. (2015)						
low-risk drivers	0,02	-0,22	-0,24	0,00	-0,02	0,04
middle-risk drivers	0,02	-0,22	-0,24	0,00	-0,01	0,14
high-risk drivers	0,02	-0,22	-0,24	0,00	-0,18	0,02

V. DISCUSSION

The goal of our work was to develop an approach to define a controllability factor for the ASIL classification during highly automated driving. Therefore we looked at different driver models and developed a quantitative model for highly automated driving. We identified different influencing factors based on the analysis of different studies on takeover scenarios during highly automated driving. Based on the qualitative model and the influencing factors we developed a flow chart and a quantifying model to predict the takeover times and define a controllability factor for a given scenario and a given system. We validated our model results by comparing the results with the takeover times from different studies and show that it is possible to model different takeover processes with one system model.

The model is able to make predictions of mean takeover times and the associated standard deviations for takeover scenarios during highly automated driving and the controllability factor for a given scenario. Since there are still differences ($\leq$ 0.25 s) between the model and the authors of the studies the prediction accuracy is limited. The deviations appear due to several reasons. The values for each action time are based on studies and values found in literature. Therefore, they represent an approximation which should be analyzed in further studies. Further, we only included influencing variables which are explicitly covered by the studies. Other influencing variables like the active-ADAS time or the daytime might have a large impact on takeover times. In this regard driver drowsiness and concentration loss have to be further investigated and implemented into the model. Lastly, the weather conditions and the experience level of the driver with ADAS are not represented in flow chart.

Since we could only consider studies with a TTE of 4-8 s, future studies have to investigate shorter and longer TTE.

These future investigations of action times and influencing variables will increase the prediction accuracy of our model. But, two restrictions of the model remain: Firstly, we assume that the mean and standard deviation values for each action are normally distributed. Espacially for reaction times a normal log distribution might be better suited. Secondly we assume, that each driver acts correctly after he gains full situation awareness. Both assumptions have to be investigated in further studies.

VI. CONCLUSION

Our goal was to develop a model, which is able to determine a controllability factor during highly automated drive. We looked at different driver models and studies on takeover scenarios and developed a new driver model, which is able to predict the mean takeover-times and standard deviations during highly automated driving. Therefore, our model is able to predict the controllability if the scenarios meet the models limits. Since we could not consider all the influencing variables, further studies on the driver's behavior and takeover have to be investigated. We showed that it is possible to model takeovers from different studies with one flow-chart-model. Such an approach could be used to introduce a standardization for takeover studies.

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