

Tools and methods for current and future controllability assessment

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ABSTRACT

Driver related evaluation of Advanced Driver Assistance Systems (ADAS) needs to address controllability, effectiveness and user acceptance, which are to some extent interfering with each other. The state of the art in the controllability assessment is currently defined by the Code of Practice of the RESPONSE 3 project which focuses on the driver-system-interaction with single assistance functions like ACC or LKA. However, the controllability evaluation of new assistance functionalities such as ADAS of automation level 2 or automated driving on level 3 (according to SAE definitions) requires a review of the existing methods and tools with regard to necessary adaptations and new developments.

For controllability evaluation of future ADAS and systems of higher automation levels the existing methodology needs to be adapted. Aspects to be considered in this context are the increasing amount of information with regards to the automation level. This information needs to be perceived and processed by the driver when interacting with multiple parallel operating assistance functions and complex information and communication systems.

The controllability of urban assistance functions and their failures is subject of discussion especially focusing on tools and methods for an urban controllability assessment. To that end, driving simulator experiments, vehicle-in-the-loop and real vehicle studies are conducted analyzing existing controllability methods on their suitability for urban assistance functions. The results show the specific advantages of each applied testing tools and suggest that an overall system evaluation addressing controllability, effectiveness and acceptance combines the advantages of the different testing environments.

Next to acceptance and effectiveness the controllability analysis is embedded in the overall evaluation process with focus on the driver and the interaction with the vehicle. The controllability analysis process for higher levels of automation is described. An overview of state of the art controllability evaluation is provided. The problem for future systems is analyzed and possible methods and tools are proposed. The necessary methods and tools are described focusing on next generation ADAS and higher levels of automated driving.

The results are limited to the driver interaction with assisted driving. For the assessment of the driver reaction to higher automation levels the use of a high-fidelity driving simulator seems reasonable to achieve a high reproducibility of the driving scenario and a good representation of the driving dynamics.

INTRODUCTION

Recently, various national organizations have proposed classification levels for vehicle automation (BAST, VDA, SAE, NHTSA). Within this paper the degree of vehicle automation is defined according to SAE [1] into

6 different automation levels ranging from manual driving (level 0) to fully automated driving (level 5). Necessary legal adaptations for the use of assistance functionalities of higher automation level are currently ongoing to build up the legal framework for their implementation. Beside this basic legal adaption evaluation methods for these functions need to be adjusted or extended since level 2 and 3 systems require the human driver as a fallback solution. Thus, an interaction between system and driver is still necessary, but may differ from previously known systems with a limited scope of system actions and system limitations. Figure 1 shows the different interaction dimensions in the control loop driver - vehicle - environment according to [2]. These are to be taken into account for the evaluation of the system. Especially the controllability evaluation at system limitations and boundary conditions or technical failures needs to be considered in order to ensure safe operation.

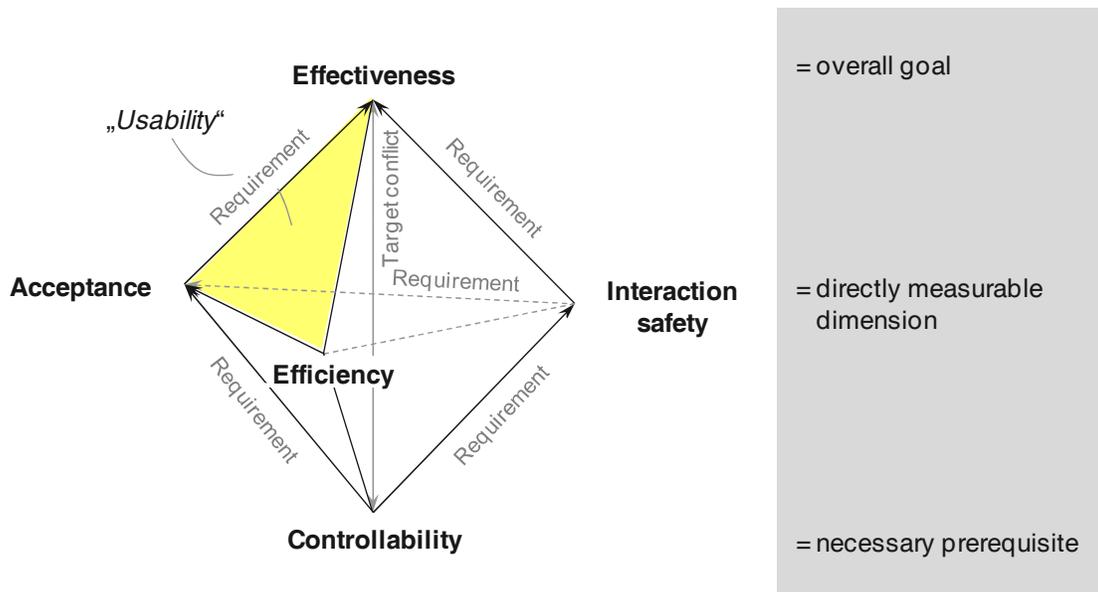


Figure 1. Interaction dimensions for ADAS and automated driving function evaluation [2]

In the following state of the art tools and methods for the controllability assessment are discussed with regards to their applicability for future assistance and automation functionalities. To that end, the current state of the art is highlighted and compared to the requirements arising from the wider operation scope of new functionalities. Necessary adaptations and new developments are highlighted and deduced to meet the new challenges.

REQUIREMENTS DUE TO NEW ASSISTANCE FUNCTIONS AND HIGHER AUTOAMTION LEVELS

The increasing automation level in new production vehicles leads to a change in the role of the driver. The SAE definition of different automation levels is therefore closely related to the responsibilities of the human driver and the system in their (timely parallel) interaction which is necessary on level 1 to 3 (see Figure 2). Level 1 assistance systems are directly addressed by the current state of the art methodical framework. In level 2 and 3 the human driver is still considered for the fallback performance of the dynamic driving task in case of system errors, failures or system limitations. Thus, for these systems the controllability by average skilled drivers has still to be proven. Systems of even higher automation levels (4 and 5) do not require the human driver as fallback solution by definition and therefore necessitate a purely technical approach in terms of the controllability even in critical situations.

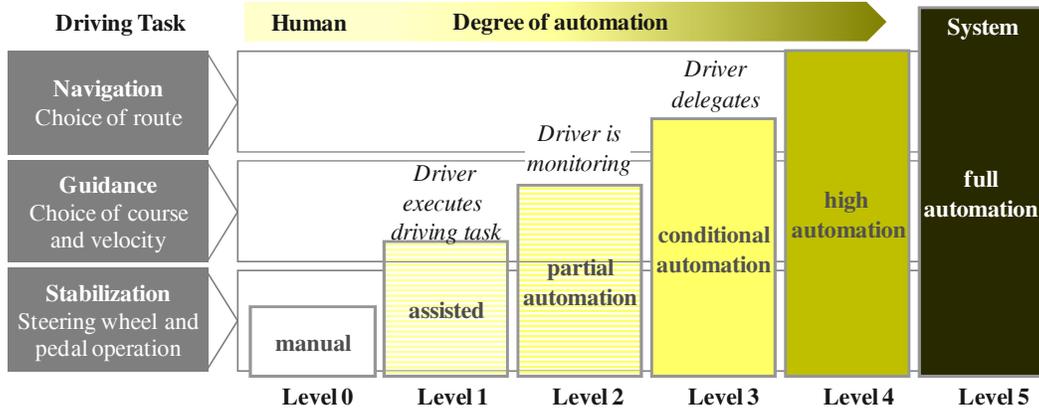


Figure 2. Definition of different automation levels

Even though the driver is still considered for the fallback performance of level 2 and 3 systems the system takes over more responsibilities which lead to a change in the driver role from an active element of the control loop to a passive supervisor. While systems of level 2 (combination of at least two ADAS such as LKS and ACC) expect the driver to constantly monitor the driving environment, level 3 systems also take over this task. In reverse, automated driving systems (level 3) provide a transition time between system and human driver so that the driver can resume to the driving task. Here, the questions arise if the driver is able to serve as a fallback solution in situations in which he is not continuously “in the loop” anymore and the overall duration necessary for a safe transition between system and driver. First insights on the necessary time frames for the takeover by the driver can be found in [3], [4], [5], [6] and indicate time spans in the range of 5 to 10 s. However, if the situation does not provide the required time for the driver to perceive and process all relevant information for a safe takeover, the driver may react inappropriately due to a panic reaction. From the human factors prospective it seems therefore doubtful, whether a safe transition between system and driver may be realizable in all conditions in automation level 3.

In addition, the increasing level of automation requires automated driving systems to cope with scenarios that require system actions in high dynamic driving situations. Thus, the system capabilities have to be widened with regard to intervention intensity and short time frames targeting an appropriate system behavior in emergency situations in which a transition time between system and driver cannot be realized. The enhanced capabilities on the other hand reduce the driver’s controllability in case of a system failure resulting in a target conflict between system effectiveness and controllability. Controllability by the driver may therefore not be achievable at any time. In this case the applied controllability criteria and even the term “controllability” need to be chosen with care. In a worst case scenario a system failure may occur while driving in automated mode and therefore while the driver is inattentive. Even in a test environment such a situation may be critical since it cannot be estimated, if the driver will react in an inappropriate manner worsening the current situation. Hence, appropriate testing tools have to assure testing of automated driving scenarios without physical risk for test subjects and prototypes.

The requirements due to new assistance functions can be summarized to:

1. New role of the driver (especially for level 3 automation and higher)
 - a. What are controllability criteria for a system that has to provide a transition time between system and driver? Is controllability by the driver achievable if the driver does not have to monitor the driving process?

- b. Driver do not have to monitor driving environment and therefore the driver might be inattentive. The current methodical framework for controllability assessment does not sufficiently consider the driver state.
 - c. Testing with inattentive driver may lead to critical situations due to unexpected driver reactions and therefore test with inattentive drivers is necessary in a environment without physical risk.
2. Enhanced system capabilities
 - a. Systems need to be able to act with higher dynamics and therefore a target conflict between effectiveness and controllability increases.
 - b. Controllability by the driver may not be achievable at any time. Therefore criteria and definition for controllability have to be adapted.
 3. Multiple parallel acting functions
 - a. Driver has to consider lateral and longitudinal control at the same time which may cause difficulty for drivers to operate both parallel (especially in critical situations)
 - b. Priorization of controllability criteria for lateral and longitudinal control

STATE OF THE ART IN CONTROLLABILITY ASSESSMENT

In the following available tools as well as the methodical framework for controllability assessment are described. The objective is to provide an overview of state of the art controllability evaluation, analyze possible problems for future systems and higher automation levels and evaluate the methodical framework and applied tools on their suitability for these systems.

Methods

The methodical state of the art in the controllability assessment of assistance functionalities is currently defined by the methods given in the ISO 26262 [7] for functional safety and the Code of Practice of the RESPONSE 3 project [8]. While the ISO 26262 has a wider scope with regards to functional safety, the CoP directly addresses the controllability evaluation of ADAS (level 2).

ISO 26262

The norm ISO 26262 addresses the functional safety of electrical and/or electronic (E/E) systems of series production passenger cars. Hence, assistance functionalities are also in the scope of the norm. In part 3 the hazard analysis and the risk assessment during the concept phase is elaborated giving methods for the identification and classification of potential hazard events. To that end, hazardous events are classified in automotive safety integrity levels (ASIL) by evaluating the severity of a potential harm, the probability of exposure regarding the operational situation and the controllability of the hazardous event.

Controllability is defined as “the probability that the driver or other persons potentially at risk are able to gain sufficient control of the hazardous event, such that they are able to avoid the specific harm” ([7]). Therefore, controllability classes are linked to the percentage of the driver collective that are able to “control” the specified situation based on pre-defined criteria (see Table 1). With regard to the content of the RESPONSE 3 Code of Practice the norm annotates that C2 classification can also be achieved by a controllability level of 85% in a practical testing experience with 20 valid data sets.

Important in context of this paper is that the norm considers the driver condition by assuming that the driver (a) is in an appropriate condition to drive (not tired), (b) has the appropriate driver training and (c) is complying with all applicable legal regulations, including due care requirements to avoid risks to other traffic participants.

Table 1. Definition of controllability classes according to ISO 26262 [7]

Class of controllability			
C0	C1	C2	C3
Controllable in general	99% or more of all drivers or other traffic participants are usually able to avoid harm	90% or more of all drivers or other traffic participants are usually able to avoid harm	Less than 90% of all drivers or other traffic participants are usually able, or barely able, to avoid harm

RESPONSE 3 - Code of Practice

Other than the ISO 26262 the RESPONSE 3 Code of Practice is not a mandatory norm but a guideline with principles that are considered by car manufactures on a voluntary basis. Also, its scope is tighter by referring only to Advanced Driver Assistance Systems (ADAS). By CoP-definition these systems “assist the driver and do not take over the driving task completely, thus the responsibility always remains with the driver” [8].

Key requirement of the CoP is the controllability which is stated to be dependent on (a) the possibility and driver’s capability, to perceive the criticality of a situation, (b) the driver’s capability to decide on appropriate countermeasures and (c) the driver’s ability to perform the chosen countermeasure (see [8]). In contrast to the ISO 26262 the CoP gives three concrete approaches to proof the controllability of an ADAS (Proof by an interdisciplinary expert panel, by a test with naïve subjects or by direct recommendation by the ADAS development team). For the final proof by a test with naïve subjects the CoP states that “absolute controllability does not exist” [8]. Based on practical experience a test scenario is considered as passed if at least 85% of at least 20 test subjects meet the previously anticipated behavior or react in an adequate way to control the situation.

In the AdaptIVe project [9] the RESPONSE 4 subproject defines requirements and next steps for an adaptation of the Code of Practice towards higher automation levels. Especially the legal requirements and liability issues are in focus of RESPONSE 4. A new CoP for automated driving might be developed in a possible RESPONSE 5 project in the future.

Tools / Test environments

Different test tool / test environments are currently known to assess the controllability of assistance functions. They vary in their complexity of the representation of the vehicle and its environment and can contribute their specific advantages at different development stages of the function development. Generally, they can be subdivided into simulative testing which uses a virtual environment for the vehicle environment and the vehicle’s movement and in real world testing that enables investigations in controlled test fields or even on public roads. Instead of a detailed description of the various types of simulative and real-world testing tools their specific advantages and disadvantages with regard to their suitability for the controllability evaluation for future assistance functions will be discussed in the following.

Simulative testing

Simulative testing tools (see Figure 3) provide the possibility to investigate the interaction between a human driver and the system especially at an early stage in the development process. Therefore, the function (or functional aspects) can be experienced by the driver even before the system is implemented in its final environment [10]. This is of high importance for system of level 3 since those systems are currently under development. At the same time, also the driver reaction to system actions can be analyzed in critical situations and critical driver behavior can be estimated without actual physical risk for test subjects and prototypes. In

addition, all types of simulative testing tools have the key advantage of high reproducibility regarding the scenario experienced by the test subjects.

The required complexity of the driver surrounding and the motion feedback suggests which type of simulative test environment is best suited for the investigation depending on the analyzed aspect. Choosing a test environment is therefore a trade-off between needed resources for the investigation and external validity. While results from laboratory studies are not directly transferable to the human behavior in real world driving they enable to estimate particular aspects of the driver reaction (e.g. reaction time in specific situations) and require only few resources. If however the aspect under investigation is influenced by the motion feedback from the vehicle dynamics the use of a dynamic or high-fidelity driving simulator becomes necessary.



Figure 3. ika simulative tools for controllability assessment

Main disadvantage of the simulative testing tools is the missing or lower validity of the motion cuing for investigations of scenarios in which the vehicle dynamics are important for the driver reaction or the evaluation of the resulting vehicle motion. This problem is addressed by the implementation of high-fidelity driving simulators (see Figure 3): With the help of a rail system on which a hexapod with the simulator dome is mounted the transversal motion of the vehicle can be realized more accurately than with a single fixed base hexapod as it commonly used in dynamic driving simulators.

In comparison to real world testing tools in driving simulators scenarios of automated driving are comparatively easy to realize because of the not necessary environment perception and the already integrated driver models. This is relevant for investigation of level 3 systems that have to proof their controllability also during automated driving.

Real world testing

Real world testing enables not just the qualitative evaluation of the driver behavior, but also the quantitative analysis of its outcome with a high validity. To that end, relevant driving scenarios are realized in controlled test fields. Figure 4 shows an example of a controllability assessment of an emergency steering assist that was conducted within the research project UR:BAN [11] with the ika test vehicle which is equipped with various sensors, actuators and processors on the ika test track. In this study the driver reaction to system initiated steering interventions in different use cases (erroneous interventions as well as normal system use) was investigated with regard to the influence of driving situation [12] [13]. Due to the triggering of the interventions by a high precision positioning a high reproducibility regarding the driving scenario was achieved.

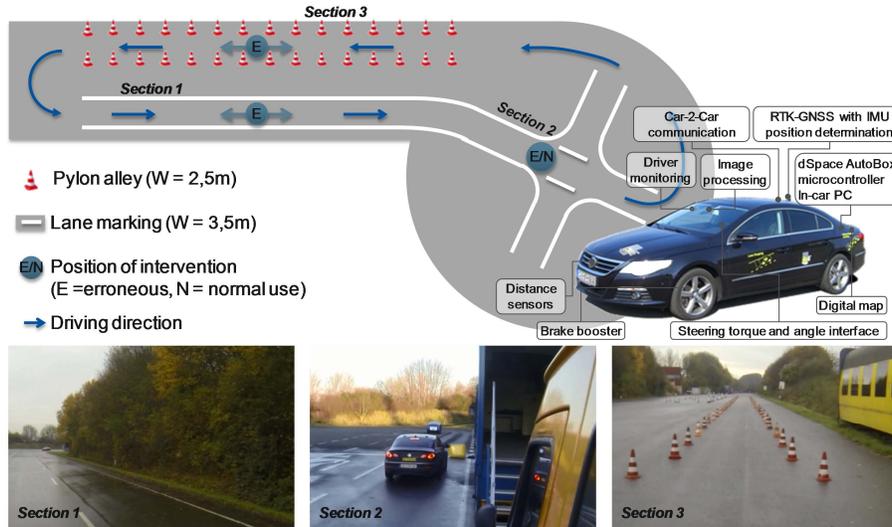


Figure 4. ika real world testing for the controllability assessment in research project UR:BAN [13]

While for most tests of systems operating on the assistance level also smaller test tracks are sufficient, controllability assessment of systems that enable automated driving require a larger test field on which these driving scenarios can be simulated without physical risk. One example for such a controlled test field is the Aldenhoven Testing Center which comprises a vehicle dynamics area, a high speed oval, a handling track and further elements (see Figure 5). Especially the high speed oval with its highway characteristic enables testing of automated systems (e.g. traffic jam assist or highway pilot) under controlled test conditions. Thus, also critical situations in automated driving scenarios can be investigated and controllability evaluation of level 3 systems can be conducted under realistic test conditions.

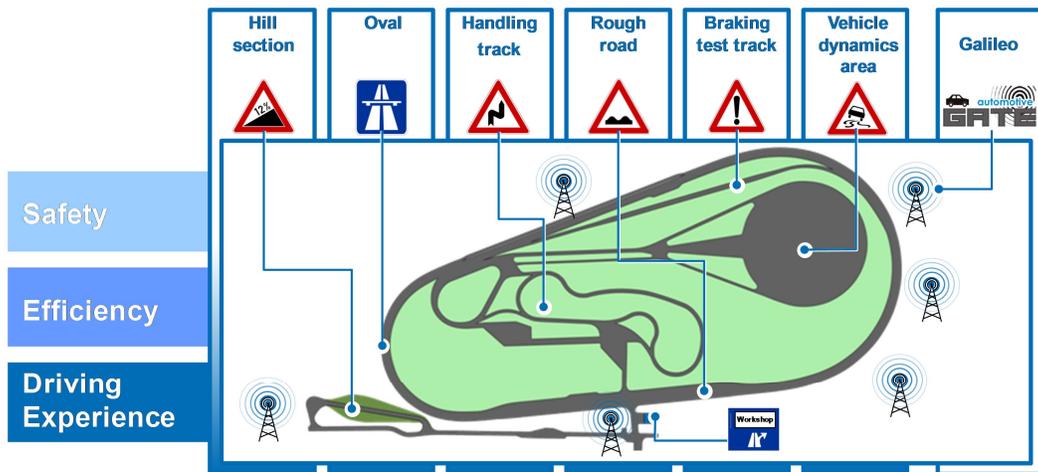


Figure 5. ATC test track layout [14]

SPECIFICATION OF NECESSARY ADAPTATIONS / FUTURE TEST METHODS AND TOOLS

Introduction of systems of higher automation levels provides challenges regarding the methodical approach for the controllability assessment. Especially at the step between level 2 and level 3 there are currently open research questions concerning the capabilities of the driver to serve as fallback solution in situations when he is not continuously involved in the driving task. Those are mainly related to the required time for a safe

transition between system and driver and the consequences if this time cannot be provided due to a critical situation. Thus, the driver state and its impact for the driver performance in controllability situations need to be considered in the methodical framework. The current assumption of an attentive driver as in the ISO 26262 is conflicting with the definition of driver's role for level 3 systems.

Due to the fact that level 3 systems need to provide a certain transition time for the takeover to the driver the systems have to deal with (critical) situations that require system interventions with high vehicle dynamics in short time frames. The enhanced system capabilities (and the related increase in effectiveness) reduce on the other hand the controllability by the driver - in particular, if the driver is inattentive in this situation. If the driver is still ought to be a fallback solution the applied controllability criteria need to be adjusted to the changed driver role. Traditional controllability criteria will not be suited for evaluation of those scenarios.

Beside the methods also the tools for the controllability assessment of higher automation systems need to be reconsidered. Like for the previously discussed methodical aspects the role of the driver influences the suitability of the presented testing tools for controllability scenarios. One of the key factors is to enable the driver to experience automated driving situations and induced a realistic driving situation with regard to the driver state at the same time. Here, driving simulators show their advantage to offer the possibility to experience automated driving at a very early stage of the development when physical prototypes not yet exist. As mentioned before systems of level 3 require the representation of high vehicle dynamics which puts the focus on the motion system of the driving simulator. Since common driving simulators are somewhat limited in the implementation of translational motion this shortcoming has to be addressed by test tools for the controllability assessment of level 3 systems (e.g. by use of high-fidelity driving simulators). If however also the motion representation of a high-fidelity driving simulator is not sufficient or thresholds have to be defined, large test fields are required to build up realistic scenarios of automated driving.

CONCLUSIONS

The increasing automation level of driving assistance functionalities suggest to review to currently applied methods and testing tools for the controllability assessment on their suitability for those systems. To that end, the paper summarized the state of the art methods and tools and compared them to the requirements for the valid evaluation of these systems. In doing so, the step from automation level 2 to 3 has been identified to provide the biggest challenges from the human factor prospective. While the methods and tools are mainly well suited for level 2 (beside system that intervene in time critical situations, e.g. automated steering in emergency situations) the change in the driver role between level 2 and 3 induces necessary adaptations, especially in the methodical framework. ISO 26262 and CoP were intended to scenarios in which the driver is actively involved in the driving task, either by fulfilling it himself or by constantly monitoring it. On level 3 the driver however can delegate the driving task to the system and has therefore not to be attentive at all times. The proposed transition time between system and driver may lead to situations in which the driver is not able to react in an adequate manner due to a critical situation.

In addition to the methods, also the testing tools for the controllability assessment were review. In general, driving simulators seem best suited for representation of automated driving scenarios since they provide the possibility to experience the automation system at an early stage in the development without physical risk for prototypes and test subjects. Here, the ability for a good representation of the vehicle dynamics was identified as one key factor since the systems capabilities have to be widened to handle also time critical driving scenarios. If a common motion system is not sufficient high-fidelity driving simulators enable to consider also scenarios that were previously only tested in controlled test fields.

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