

A New Method and Results for Analyzing Decision-Making Processes in Automated Driving on Highways

Eugen Altendorf, Constanze Schreck and Frank Flemisch

Abstract While automated driving and advanced drivers' assistant systems (ADAS) become increasingly widespread, the human machine interaction for these technologies gains in importance. In today's traffic, some vehicles are capable of driving partially, conditionally or highly automated, at least in certain traffic situations, such as driving on developed highways. Nevertheless, these technologically advanced systems are not the only participants in traffic. With the interplay of more or less technologically advanced vehicles and humans on bikes and on foot, complex situations can arise that exceed the capabilities of an automated system and requires human cognition as a part of the solution. Although ADAS and automation solutions take this into account and try to compensate for the resulting effects, encounters with ambiguous situations can emerge. Furthermore, automation systems heavily rely on sensors and are therefore vulnerable to ambient conditions and situations that might limit the performance of the used sensor technology. For this reason, the (human) driver is still required for supervising the situation and often also as a fallback level in the case the technical system reaches or exceeds its performance restrictions. Guiding a vehicle, such as a car with partial or conditional automation, entails a different kind of driver vehicle interaction and cooperation between driver and automation as the one that is needed in the case of manual driving. For analyzing the decision making process of a human-machine-system with such an advanced automation during a typical driving situation like an take-over situation on a highway, a study addressing partially and conditionally/highly automated driving was conducted. The experiment with 30 participants consisted of three rounds with varying conditions in the driving simulator. During and after each round, participants were asked to answer several questions. For this purpose, a questionnaire has been developed to measure the relevant dimensions of the investigated driving situation. These were perceived utility, perceived time consumption, perceived safety, user satisfaction, perceived usability, and perceived

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dominance (control over the vehicle guidance). The evaluation of the driving experiment shows that the level of automation as well as the volume of traffic have a significant effect on the decision-making behavior and on the individual perception when driving on a highway. This means that during automated driving, humans perceive and judge the driving situation differently. As a consequence, they tend to use the remaining decision authority for other purposes than when driving manually.

Keywords Automated driving · Advanced driver assistance systems (ADAS) · Human cognition · Decision-making · Human-machine interaction

1 Automated Driving and Cooperative Vehicle Guidance and Control

Over the last two decades, developments in advanced driver assistance systems (ADAS) and automated driving make the idea of a partially self-driving vehicle not only a research topic, but a reality on public roads. Today, several vehicle manufacturers offer cars on the market that are capable of driving automated on certain types of roads such as highways. Besides of the technical challenges of building and improving state of the art vehicle automation systems, another crucial challenge in this field becomes increasingly relevant. Since both, a human driver and a technical system, are steering the same vehicle, a multitude of complex technical functions have to be integrated in such a way that the human driver intuitively understands them. Considering that the level of automation is switched depending on the circumstances such as the state of the technical system or the environment, maintaining the driver's mode awareness is utmost important for keeping the driving situation safe. Furthermore, automation systems heavily rely on sensors and are therefore vulnerable to ambient conditions and situations that might limit the performance of the used sensor technology, e.g. the weather or unexpected objects. As a result, in many areas and situations the human driver is still needed. By designing automation systems that address such questions, the barriers between assistance systems and sophisticated automation solutions become blurred. Accordingly, complementing degrees of assistance and automation have been defined (e.g. [1–3]). For this reason, both cognitive compatibility and trust become paramount as they describe the way a human can be involved within the loop of the automation and with the automation or assistance itself (cf. [4, 5]). The development of systems that are cognitively compatible and trustworthy from a user's point of view can be supported by considering the user early in the development process [6]. These are the issues addressed by the concept of cooperative guidance and control, which is generic in describing the general degrees of freedom in the cooperation between the human and the automation as different levels of vehicle guidance and control. The H-Mode can be seen as a specific implementation of this concept. The H-Mode is

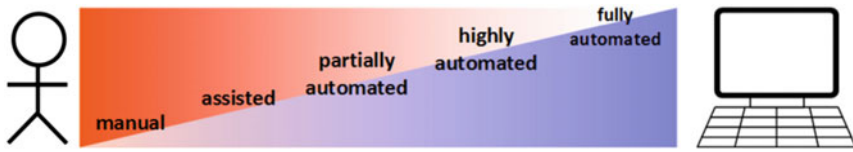


Fig. 1 Assistance and automation scale (based on [7])

based on the H-Metaphor, a design metaphor similar to the desktop metaphor for PCs [7]. It holistically describes the system behavior and the interaction and cooperation between partially as well as highly automated vehicles and the human driver. The H-metaphor draws its inspiration from the biological archetype of rider-horse or driver-carriage, where the driver can take the horse on the tight or the loose rein. A more extensive discussion of cooperative vehicle guidance and control can be found in [8, 9] describes the H-Mode in more detail (Fig. 1).

2 Guidance, Control, Responsibility and Decisions

Donges [10] introduces a three layer model of how human drivers conduct vehicles. Combined with general models of human performance [11] and on the interaction with automated technical systems [4, 10] apply models in the context of vehicle guidance and control. Donges [10] introduces a three-layered model for the sub-tasks that occur during driving. According to this model, there are the levels of stabilization, guidance, and navigation. Technically speaking, the second level, guidance, can be integrated as anticipatory control in the system [12]. An enhancement of the Donges-model can be found in Loeper et al. (2008), who add two sublayers within the level of guidance, i.e. the maneuver and the trajectory level. Thereby, they achieve a four-layered model of vehicle guidance and control, consisting of state control, trajectory planning, maneuver planning, and navigation. In this context, maneuvers can be understood as spatially and temporally related processes. In order to create a system with inner compatibility, the automation needs to follow the cognitive design laid out by this four-layered model for human drivers and needs to be constructed of similar levels.

In this paper, we mainly deal with the partially/highly-automated modes of cooperative guidance and control. In this driving mode, the vehicle takes over the tasks of stabilization and trajectory planning, but the human driver still decides about which maneuvers to be executed. The division of tasks is thus sequential along the levels that occur during driving with the automation taking care of the lower levels of trajectory planning and control, and the human focusing on the higher levels of maneuver planning and navigation.

Since vehicle guidance and control is executed on several different levels by different entities, complex decision making processes emerge. A very common situation would have the technical system taking over all aspects of vehicle

guidance on the control level, while human driver and technical system plan and act together on the guidance level. Hereby, the human driver could decide about the maneuvers, such as a lane change, whereas the sensors of the vehicle analyse the environment and make suggestions to the human driver based on their scans. In this or any comparable situation, the decision making process is influenced by the evaluation of the technical system as well as by the human judgement. For supporting efficient and target-oriented decision making processes, the evaluations of the technical system should be communicated in a cognitively compatible way. Along the same lines, the basic characteristic, which is used for assessing driving situations, should be compatible between both partners, the human and the machine. In order to achieve this, a common and comparable goal and value system is very helpful, in which the technical system should map the human evaluations. To be able to systematically analyze these attitudes of human drivers in relevant driving situations, we have developed a questionnaire, which addresses the dimensions utility, time consumption, safety, user satisfaction, usability, and dominance. In addition to this, we use of one-dimensional scales for rating driving situations with respect to the dimensions use, safety, and time without interrupting the driving experience.

3 Measuring Acceptance and Intention

In 2015, a study using the driving simulator of IAW RWTH Aachen was conducted ($n = 35$). The average age has been estimated at nearly 29 years ($SD = 8752$). The simulation included a truck as a vehicle steered by an active sidestick. The study contained three phases. The first treatment was an almost manual ride with minor assistance systems such as emergency braking (Manual Mode with an additional light assistance, which prevented to drive on the verge of the motorway). The second and third treatment consisted in each way of a ride on the same track using the more extensive Loose-Rein (partially automated) automation level. The traffic situation varied between treatments two and three in a way, that each participant took a ride in Low Traffic as well as High Traffic in Loose Rein Mode.

Each phase was followed by an online questionnaire, where, among others e.g. socio-demographics, six different scales consisting of several items have been investigated on a seven-point Likert-scale. Hereby, 1 is the lowest rating, whereas 7 is the highest approval rating [13]. Furthermore, during the Loose Rein treatments the participants were asked questions about driving situation they have just experienced, more precisely overtaking manoeuvres. They were to evaluate their experiences on the dimensions of total satisfaction, perceived timing of the overtaking process as well as perceived safety. The evaluation was carried out on basis of a scale from 0 to 100 % whereby in any case 100 % means the best evaluation and 0 % the worst. All in all the aim of these assessments is to measure effects on acceptance in decision making processes what can be derived from correlations in between the different scales raised. In this chapter the starting point and final design

of the online questionnaire and the interview are presented as well as first results concerning reliability of the different scales.

3.1 The Online Questionnaire: Starting Point

The central objective of the present study was to measure acceptance and intention of the driver towards automated driving and cooperative vehicle guidance and control in decision making processes. For this purpose, extensive research on previous studies concerning ADAS and automated driving was performed. Furthermore, studies regarding consumer products in a broader sense (e.g. software, hardware, cell phones, websites) with focus on usability and acceptability aspects as well as perceived ease of use were included. Out of this pool of different investigations similarities relating to the measured dimensions were extracted. The outcome were six scales consisting of different numbers of items depending on the findings of the research on preceding studies. The investigated scales are

- Perceived Utility
- Perceived Time Consumption
- Perceived Safety
- User Satisfaction
- Perceived Usability and
- Perceived Dominance (Control over the Vehicle Guidance).

The origin of each item is presented in the chapter below.

3.2 The Online Questionnaire in Detail

The questionnaire being used covers six scales consisting of 41 items which were all requested by a consistent 7-point Likert scale (“I strongly disagree” to “I strongly agree”). Some of the 9 original questionnaires were (loosely) translated from English to German. If the items were originally formulated as semantic differentials, they were modified into questions that can be answered by a Likert-Scale.

Furthermore, at the beginning of each experiment, sociodemographic data were collected (age, gender, if the participant is holding a driver license and for how long, if the participant owns a car, how often the car is used, the annual mileage and the usage of driver assistance systems) (Table 1).

Perceived Utility. The measurement of perceived utility includes 13 items, adopted from several previous studies.

Table 1 Average of Cronbach Alphas of the 6 scales measured

Scale	Number of items	Cronbach α (average)
Perceived utility	13	0.925
Perceived time consumption	4	0.722
Perceived safety	7	0.835
Perceived user satisfaction	3	0.852
Perceived usability	7	0.897
Perceived dominance	6	0.743

The questionnaire by Van der Laan et al. [14] was originally designed for the measurement of acceptance of new technologies, such as in-vehicle systems or advanced telematics. Van der Laan et al. have observed a high degree of correlation of the scale (Cronbach's α between 0.73 and 0.94). The items were tested in six different experiments (four in a driving simulator, two on the street), and they were found to be highly reliable. For our questionnaire, we use four items of the questionnaire by Van der Laan et al. [14]. The following items were used (the italic words in brackets show the actually chosen judgement):

- "My judgements of the system (...) are pleasant/unpleasant" (*pleasant*);
- "My judgements of the system (...) are useful/useless" (*useless*);
- "My judgements of the system (...) are assisting/worthless" (*I think there is a real added value with respect to conventional vehicles*);
- "My judgements of the system (...) are effective/superfluous" (*effective*).

The Technology Acceptance Model (TAM) by Davis [15] is a well-known model for user acceptance, similar to the Unified Theory of Acceptance and Use of Technology (UTAUT) by Venkatesh and Bala [16], Osswald et al. [17] have refined these two models to be better applicable to the automotive sector by introducing the Car Technology Acceptance Model (CTAM). Thereby the following 8 factors were created and measured on a 7-point Likert Scale (0 = not at all applicable, 6 = totally applicable): Performance expectancy, Effort expectancy, Social influence, Facilitating conditions, Self-Efficacy, Anxiety, Perceived Safety and Attitudes Towards Using Technology. The items Performance expectancy and Perceived safety were assumed for the present study. The two items taken from [17] were lightly modified in a way that they refer to the vehicle as a whole and not only to the assistant system. The final items are

- "The vehicle increases my driving performance" and
- "Driving this vehicle is very comfortable."

The Technology Acceptance Model (TAM) by Davis [15] was also used by Lund [18] to measure the Usability of consumer products. 6 of 30 items were used in the present study for the scales of perceived usability and perceived time consumption. Thereby five items were adopted from [18]. We specified the question to refer to the vehicle in the situation the participant has just experienced, so we

replaced “it” by “the vehicle”. The following items were used in the present investigation:

- “The vehicle does everything I would expect it to do”;
- “The vehicle meets my needs”;
- “The vehicle makes the things I want to accomplish easier to get done”;
- “The vehicle is useful”;
- “The vehicle helps me be more productive”.

Two items, which were developed by Trommer and Hörtl [19], were used to measure perceived time consumption, which is in the coming paragraph, and perceived utility. The original and standardized questionnaire (n = 5807) was generated for the project eCoMove, which was a study in 11 European countries concerning a navigation wizard (assistant) to reduce CO₂ emission. The following item was taken from [19] and also changed in the sense, that it refers to the vehicle as a whole.:

- “The vehicle restricts my freedom while driving”

The last item of the perceived utility scale was loosely based on an item by Ussat [20]. For measuring the acceptance of an assistant system or rather of a ubiquitous system, [20] has utilized a questionnaire by Rothensee [21]. The UbiTAM allows to collect data concerning the impact on driving performance and the quality of the given task, in this case a driver assistance systems for the personalized choice of destination. One item was adopted for the scale of perceived utility in the present investigation which was originally developed by Davis [15]:

- “I am satisfied with the vehicle guidance”.

The total reliability of the scale of perceived utility is excellent (average: $\alpha = 0.925$).

Perceived Time Consumption. The Perceived Time Consumption scale measures the subjective evaluation of timescales in the situation the participant has just experienced. For this purpose, four items were used. The first is adopted from Trommer and Hörtl [19] and rotated so that “The system saves travel time” was modified into:

- “Driving with this vehicle extends travel time”.

The second item, originally by Osswald et al. [17], was adapted to the background of investigation. According to this “Using the system enables me to accomplish my goals more quickly”, was changed into

- “The vehicle enables me to reach my final destination more quickly”.

Third, an item by Lund [18] (originally: “It saves me time when I use it”) was adapted:

- “Driving with this vehicle saves time”.

Finally we formulated an item on our own to measure implicitly the actual perceived time consumption in the situation the driver has just experienced:

- “The vehicle helps me to get through the traffic in time”.

The total reliability of this scale is acceptable (average: $\alpha = 0.722$).

Perceived Safety. The third scale “perceived safety” was measured by eight items, whereby six of them were adopted by Osswald et al. [17]. Five of them were originally created to measure “perceived safety”. The items were:

- “I believe that using the system is dangerous”;
- “Using the system requires increased attention”;
- “The system distracts me from driving”;
- “I feel safe while using the system”;
- “Using the system decreases the accident risk”.

The last one was originally used to measure “performance expectancy” but covers also security aspects:

- “If I would use the system I will reach my destination safely”.

In a pilot project, [22] have developed an online questionnaire to identify diffusion, publicity, utilization, and perception concerning driver assistant systems as well as experiences and expectations of elderly drivers with driver assistant systems. Among other things, the subjective feeling of safety and the influence of the assistant systems were determined. One item regarding perceived safety was adopted. They have compared the perceived safety of different assistance systems with their questionnaire. For each driver assistance system a subjective assessment of the driving behavior was requested. In its original version, the question was “Do you think that the driver assistance system has an influence on how carefully you are driving? Please give an evaluation for each system.” The response options were: “I rather drive more carefully/I drive as carefully as always/I drive rather less carefully/I don’t know”. A modification of this item was made:

- “I rather drove more carefully with this vehicle.”

In a simulator study by Comte [23], two systems of speed check (Fixed system and Dynamic System) were compared to an “advisory system” and a “baseline control” (which means “no system”). Besides the semantic differentials by Van der Laan et al. [14] and the NASA-RTLX by Hart and Staveland [24], which were used in Comte’s investigation, an Acceptability Questionnaire was developed to measure the attitude of the participants concerning the assistant system. Finally one item was used:

- “In your opinion, would this vehicle make people commit less offences?”

The total reliability of the scale of perceived safety is good (average: $\alpha = 0.835$), when leaving out the item “I rather drove more carefully with this vehicle” (otherwise $\alpha = 0.768$).

User Satisfaction. To measure the scale of user satisfaction, again three semantic differentials by Van der Laan et al. [14] were reformulated into questions which can be answered on Likert scales:

- “My judgements of the system (...) are undesirable/desirable”, was turned into “Driving with this vehicle is desirable”.
- “My judgements of the system (...) are nice/annoying”, was changed into “Driving with this vehicle is nice”.
- “My judgements of the system (...) irritating/likeable” was modified into “Driving with this vehicle is irritating.”

The total reliability of the scale of User Satisfaction is good (average: $\alpha = 0.852$).

Perceived Usability. To evaluate the scale of perceived usability seven items were taken from Brooke [25] who developed the System Usability Scale (SUS) to gain a comprehensive view on the subjective evaluation of usability in the context of software systems. Brooke has chosen the final 10 items out of a pool of initial 50 items, which showed a high degree of correlation. 7 of the final 10 items were utilized in the present investigation. (“The system” was always replaced by “the vehicle”.) The items being used are:

- “I found the vehicle very cumbersome to use”;
- “I would imagine that most people would learn to drive with this vehicle very quickly”;
- “I thought there was too much inconsistency in this vehicle”;
- “I found the various functions in this vehicle were well integrated”;
- “I thought the vehicle was easy to use”;
- “I found the vehicle unnecessarily complex”;
- “I think I would like to use this vehicle frequently”.

The total reliability of the scale of Perceived Usability is good (average: $\alpha = 0.897$).

Perceived Dominance. For the last scale “Perceived dominance” six semantic differentials by Mehrabian and Russell [26] were transformed into statements that can be handled with Likert scales. Mehrabian and Russell [26] have created six semantic differentials which are introduced as follows: “Please rate the feelings in the previous situation with the following adjective pairs. Some of the pairs might seem unusual, but you will probably feel more one way than the other. So, for each pair, put a check mark close to the adjective which you believe to describe your feelings better. The more appropriate that adjective seems, the closer you put your check mark to it.” The original differentials were: “controlling/controlled; influential/influenced; important/awed; in control/cared-for; dominant/submissive; autonomous/guided”. On this basis, the following items were constructed:

- “The vehicle controls me a lot”;
- “The vehicle has influenced me a lot”;

- “I have dominated while driving with this vehicle”;
- “I felt influential while driving with this vehicle”;
- “I had control while driving with this vehicle”;
- “The vehicle guided me while driving”.

The total reliability of the scale of perceived safety is acceptable (average: $\alpha = 0.743$).

3.3 *The Interview During Ride*

The background of this interview is the RSME developed by Zijlstra and van Doorn [27] even though in an extensively modified way. The rating does not concern mental effort, which is the aim of RSME, but subjective evaluations of the situation just experienced. Also the participants were not to put a mark on the scale on their own, but had to specify a value which was noted by the investigator, because the ride should not be interrupted. The justification of the engaged interview concentrates on the following point:

“The importance of subjective experiences goes beyond the issue of subjective ratings. The phenomenological experiences of human operators affect subsequent behavior and thus also their performance and physiological responses in a given situation. If operators consider the workload of a task is excessive, they may behave as though they are overloaded, even though in all objectivity the task demand is low.” [28].

Transferred to the situation of the study presented in this paper: Even if it looks like an overtaking maneuver went very well (e.g. no crash, no delay of traffic), the assessment can be different for the driver. Safety and satisfaction are highly subjective estimations so one cannot say that 100 % of satisfaction means the same for all participants, but it is possible to compare the estimations of one single participant, also with her evaluation by the online questionnaire to make reliable statements.

The participants were informed to be interviewed about their subjective evaluation of various overtaking maneuvers. They were asked three questions directly after initiating to overtake another vehicle and had to answer them on a scale from 0 to 100 % (all conceivable steps between 0 and 100 % were possible). Besides, the meaning of these questions were explained to each participant. The questions were:

- “All in all, how satisfied are you with this driving situation?”;
- “How satisfied are you with the timing of this driving situation?” (That means: “Did it go fast enough? By your feeling, were you thwarted in an uncomfortable way?”) and at last
- “How safe did you feel within this driving situation?”.

A value of 100 %, in any case, corresponds to the best evaluation (100 % of total satisfaction, 100 % of satisfaction with the timing, and 100 % of safety.). Each participant had to complete 20 overtaking maneuvers, but they were not informed about this amount.

4 Conclusion and Outlook

In this paper, we have presented how a questionnaire for experiments in the field of automated vehicles can be structured. We have identified six scales that can help the investigation of the driving experience and the analysis of the underlying decision making processes when guiding an automated vehicle through highway traffic. The scales were perceived utility, perceived time consumption, perceived safety, user satisfaction, perceived usability, and perceived dominance. Using the experimental data, we could show that the reliability of the scales, as measured by the Cronbach's alpha is acceptable to outstanding in all cases. By complementing the resulting comprehensive online questionnaire with repeated ad hoc questions, a more detailed picture of the user experience could be obtained. This can be helpful when looking into possible user acceptance of the systems, i.e. vehicles, studied.

The questionnaire is meant to serve as a basis for further experiments in the field. Future research can refine the proposed scales and add new scales, such as one concerned with ecological issues, monetary values, or the added-value of leisure time during the ride.

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