Partially Automated Driving as a Fallback Level of High Automation

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***Abstract*— When reaching a system limit, highly automated vehicles arbitrate control back to the driver. In some situations, a complete arbitration to the driver may not be appropriate or favored and a monitoring of the system sufficient. This study verifies the opportunity to use partial automation as a fallback level of high automation. Furthermore, monitoring with hands on the steering wheel is compared to monitoring solely visually. A study with 32 subjects and another 16 subjects in the baseline condition was conducted in the dynamic driving simulator of the BMW Research and Technology. In two out of six situations, subjects had to take over control after monitoring the system for two seconds in a time critical situation. A faster intervention with less braking and acceleration was observed in the baseline group compared to the automated condition. Nevertheless, concerning the subjective rating of the subjects, the partial automation was considered as comfortable and useful. Concerning the type of monitoring, hands on the steering wheel led to a 0.3 s faster intervention without statistical significance (p=0.158; r=0.234).**

Automation, Transition, Take-Over, Driving, Automated vehicles, Driving simulation, System monitoring

I. INTRODUCTION

The first highly automated vehicles from various automobile manufacturers are being tested on public roads. Highly automated driving in a series vehicle seems to be achievable within a couple of years. As automation in vehicles increases and driving tasks are passed over to the vehicle, automation effects appear that are known from other domains, such as aviation or production. For instance, Nilsson discovered problems with mode awareness in the context of Adaptive Cruise Control (ACC) [5] and Desmond, Hancock and Monette found impairments on driving performance through automation in vehicles [2], similar effects that are already known from aviation (e.g. [7]). Furthermore, Stanton and Young stated, that "participants using automation were more likely to be involved in a collision than when driving the car under manual control" [8]. Such studies demand a closer look at possible automation effects in passenger cars and ways to prevent negative impacts on driver's safety. There are and will be situations in the future that automation will not be able to handle (system limits). In such situations the driving task has to be allocated back to the driver. Since drivers are no longer directly involved in the driving task, situations may be critical and time to regain control is very limited, those take-over situations will be one of the most crucial aspects of vehicle automation in the future. There are few publications concerning taking over control from the automation in passenger cars. Damböck et al. compared different take-over situations as a function of three different time budgets [1]. Petermann and Schlag compared different transitions between five automation levels concerning mode awareness, complexity and system transparency [6]. Gold et al. consider different time budgets and the transition from high automation to manual driving [4]. This transition prevents problems with mode confusion since the task is clearly assigned either to the driver or the automation. A disadvantage is that the driver is not supported by any assistant system after the take-over. For some uncertainties of an automated system, a monitoring may be sufficient and a complete take-over inappropriate. Thus, substituting take-over requests by a monitoring-prompt may increase comfort level and satisfaction of drivers. This study was conducted in the dynamic driving simulator of BMW Group Research and Technology to check whether a transition to partial automation brings benefits.

II. EXAMINATION QUESTION

The examination question is based on the assumption that there will be system limits in future vehicle automation systems which require the intervention of the driver. In "high automation" the driver does not have to monitor the system the whole time, but be able to take over control with an appropriate time budget [3]. An example for a take-over would be a person next to a highway whose intention is not detectable by the system. In such situations a complete arbitration of the driving task to the driver may not be appropriate. The system can still perform guidance, but cannot forecast how the situation will evolve.

There are two possible ways to monitor the system. The driver can either visually monitor the system or additionally put his/her hands on the steering wheel to get further involved in the driving task without making any input. In either case, automation that has to be monitored is called "partial automation" [3].

The two main questions of this examination are:

- Is there a possibility to improve the Human-Machine System by introducing a transition from high to partial automation in uncertain situations?

- Is there a difference between solely visual monitoring and visual plus motoric monitoring?

III. METHOD

A group of 32 subjects went through a highly-automated driving scenario in a high fidelity driving simulator of BMW Group Research and Technology and had to react to monitoring requests (MR). A second group of 16 subjects went through the same scenario, but without any assistance of the automation, in order to create reference values.

A. Simulation and test subjects

Simulator. The high fidelity driving simulator consists of a motion-based, full vehicle mockup with approximately 240 degree field of view. The rear visibility using the side mirrors is implemented by one projector for every mirror. A display directly behind the vehicle's back seats provides an image for the rearview mirror. All relevant driving data (recording frequency 100 Hz), including hands-on detection and the input on the control elements, the instrument cluster, and a video of the driving scenery, are recorded. Additionally, the mockup is equipped with three cameras observing the driver and his/her reactions from different angles. Moreover, the subjects wore a head-mounted eye tracking system (Dikablis) to track their gaze behavior (recording frequency 25 Hz).

Subjects. The 32 subjects were employees of the BMW Group and between 19 and 57 years old (Mean=27.6 years; SD=8.7 years). Eight subjects were female (25%) and 24 male (75%). Fifteen subjects had experienced a driving simulator before (47%) and hence were familiar with the characteristics of simulated driving. Another two subjects participated in the study, but could not be considered due to aborts caused by kinetosis and technical problems.

Baseline. A baseline study was conducted with a second group of 18 subjects. Two of them had to be disqualified because of kinetosis and technical problems. The remaining 16 subjects, also BMW Group employees, were between 20 and 55 years old (Mean=28.5 years; SD=10.0 years) and consisted of 12 male (75%) and 4 female (25%) participants. Because the gaze behavior of manually driving subjects is not comparable to those driving highly-automated, the gaze behavior was not measured here.

B. Automation

The implemented automation was derived from the definition of automated driving from Gasser [3]. The car controls longitudinal and lateral guidance and does not have to be monitored as long as it does not prompt any MR. Furthermore, automation performs lane changes and overtakes slower vehicles. The maximum speed was set at 120 km/h. As soon as the car detects a system uncertainty it prompts a monitoring request (MR). Starting from this MR, the driver has a certain total time budget (TTB) to start monitoring the system or take action before reaching the reason of the system's uncertainty, like a person next to the highway. For a short TTB the performance of the driver decreases drastically (compare [1], [4]). However, the maximum TTB is limited by the in-vehicle sensory systems of the vehicle. Only after the uncertainty is detectable for the system can an MR be prompted. A reasonable TTB of six seconds was chosen for the study. This TTB is based on an estimation of future in-vehicle sensor range and selected to measure the performance of the driver.

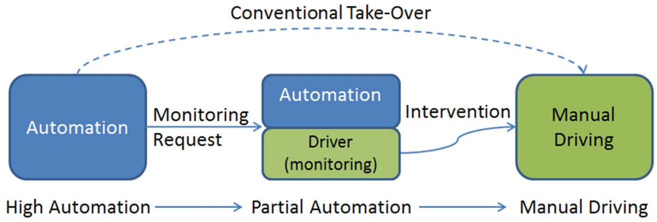

Figure 1: Automation states and transitions

The system state was displayed by symbols in the instrument cluster and the MR was provided acoustically and optically, in order to enable a fast reaction.

C. Course Design

The track consisted of six situations representing system uncertainties, implemented in a European three-lane highway with a 120 km/h speed limit.

Situations. To assess the performance of the driver, two out of the six situations evolved critically and required an intervention of the driver. Figure 2 shows the procedure of these critical situations. The vehicle prompted an MR six seconds before reaching system uncertainty. After two seconds, and therefore four seconds before reaching system uncertainty, the situation suddenly became critical. Although the TTB was six seconds, the subjects had four seconds to detect the boundary and intervene.

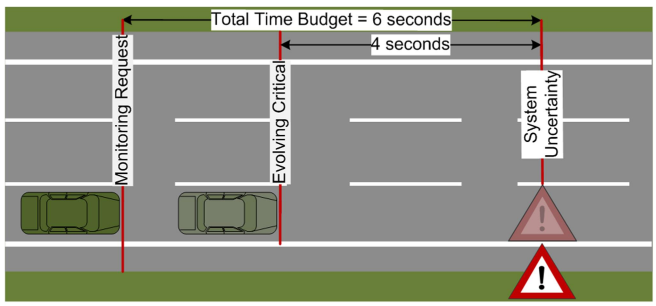

Figure 2: Procedure of situations

Situation Person. In this situation the ego-vehicle was driving on the right lane with a speed of 120 km/h with a leading vehicle to cover the situation. A car with a breakdown, located on the hard shoulder, and a person in front of this car were representing the uncertainty. Six seconds before reaching the car, the ego-vehicle prompted the MR and simultaneously the leading vehicle passed und revealed the situation. Four seconds before reaching the car, the person behind the car started to walk and entered the lane of the ego-vehicle. The participant either had to brake or change lanes to prevent a possible collision with the person. For ethical reasons, the person stops one meter inside the lane, so that a very few centimeters distance remains to the side mirrors and the car does not hit the person if the driver does not intervene.

Situation Road Construction. This second situation was designed similar to "situation person". The uncertainty was represented by road construction on the hard shoulder and the situation becomes critical when a compressor rolls into the lane, with the same trajectory and timing as the person in the other situation. The compressor is not covered behind any other object, as you would not expect a still standing trailer to begin rolling.

Uncritical Situations. In addition to the situations evolving critically, there were four other situations implemented to clarify that not every MR requires an intervention. In these situations the MR also emerged six seconds before the uncertainty, but evolves uncritically. Two of these situations are similar to the critical situations and differ only slightly in their appearance. One of the remaining situations was represented by a driver on the next lane, swerving in his lane while he was overtaken by the subject. In the last uncritical situation a lane narrowing caused by a road construction was detected as a system uncertainty. These situations are not described further, since they are not analyzed.

D. Conduct

All 32 participants, after getting familiar with the dynamic of the simulation and automation in an extra course, experienced all six situations included in one course. The order of the situations was permuted between the subjects, with the constraint that the first two situations had to be uncritical ones and there had to be at least one uncritical situation between the two critical ones. The track was approximately 28 minutes long, so that the average time gap between the situations was about four minutes.

Looking at the controllability aspects of automated driving, it has to be considered that as soon as the driver does not have to monitor the system, he/she can do everything. Therefore, the ISO-standardized visual-motoric Surrogate Reference Tasks [9] is implemented in this study. The task was provided sequentially for about 1 minute at one minute intervals and presented alternatingly on a handheld nomadic device (tablet computer) or in the center console. The subjects had to perform the SuRT for at least 20 seconds before any MR arises. Between the situations, there was a varying number of SuRT Tasks without any MR in order to make the MRs more unpredictable.

After the MR, one-half of the subjects were instructed to only visually monitor the system, the other half to monitor the system and return their hands to the steering wheel.

Another group of 16 subjects drove the same course manually and without any assistance. This baseline serves as a reference for the main study.

E. Measurements

The performance of the subjects was measured objectively by eye tracking, driver's input and driving parameters and subjectively by short interview questions after each situation and a final questionnaire.

The first reaction to the MR (Gaze reaction), the first gaze on the street (Road fixation), and the gaze behavior to secure a lane change (Side mirror) were registered using eye tracking. Other reaction times that were recorded were the point in time when the hands touched the steering wheel (Hands On), the first conscious input (Intervention) and the operation of the turn signal (Turn signal). Table 1 summarizes the different reaction times.

Table 1: Reaction times

Gaze reaction	Time between MR and first saccade generated by the SuRT
Road fixation	Time between MR and first gaze at scenery
Hands on	Time between MR and first contact between driver and the steering wheel
Intervention	Time between MR and the first conscious input made by the driver. To exclude unintentional inputs and inputs for vehicle stabilization, reasonable limits are: >2° steering wheel angle >10% braking pedal position
Remaining action time $=TTB- T_{intervention}$	Remaining timeframe (time to collision) to perform a lane change or brake until full stop at the time of intervention.
Side mirror	Time between MR and first gaze at the left side mirror
Turn signal	Time between MR and the operation of the turn signal

Accelerations can be analyzed to assess the driving maneuver. The higher the accelerations in the longitudinal and lateral directions, the more forces the tires have to transfer. With high accelerations the car is moved closer to the physical limit and the executed maneuver is more critical. Therefore lateral accelerations are considered, as well as a combination of lateral and longitudinal accelerations, in order to measure lane change performance. The combination of lateral and longitudinal accelerations is called Utilization of acceleration potential and follows the "circle of accelerations" [4]:

$$a_c = \sqrt{{a_{long}}^2 + {a_{lat}}^2}$$

IV. RESULTS

The 32 subjects experienced each situation once. By this, 32 measurements for the situation person, as well as for the situation road construction were generated. Since the leading vehicle could not cover the situations in total and some subjects tended to check the scenery occasionally, some subjects spotted the situation before the MR arose, which was apparent in the eye detection data. Since these subjects had more time to gain situational awareness, they were excluded from the analysis. In the baseline group, some subjects reacted to the situation itself before the situation evolved critically. They changed lanes to increase the distance to the potential risk source. Although this behavior might be reasonable, these subjects are not considered in the results to the detriment of the results of the baseline group.

The remaining situations in the automated condition can be divided into groups of subjects who were instructed to monitor either visually or motorically, with hands on the steering wheel. Not every subject followed these instructions and some changed their behavior. For evaluation, the subjects were grouped depending on how they actually monitored each situation, not how they were instructed to monitor. An overview is given in Table 2.

As mentioned before, the SuRT was presented in the center console for one half of the subjects; for the other half the SuRT was handheld on a nomadic device. Since there has not been any significant difference in the considered factors with this experimental design, the location of the task was not further considered in the evaluation.

Table 2: Considered subjects

	Automated Condition				Baseline	
	Construction		Person		Const.	Pers.
Subjects in total:	32		32		16	16
Subjects that did not see situation before MR:	25		28		14	11
Sorted by actual monitoring:	Vis. 15	Mot. 10	Vis. 18	Mot. 10	/ /	/ /
Did not intervene:	3	1	7	1	/	/

A. Reaction Times

Reaction times were analyzed for the visual and the motoric group. Visual and motoric monitoring were merged and compared to the reaction times in the baseline group to compare the automated condition with the baseline. The results are shown in Figure 3. As the Hands On-Time is not comparable between the visual and motoric group, these results are shown in parenthesis.

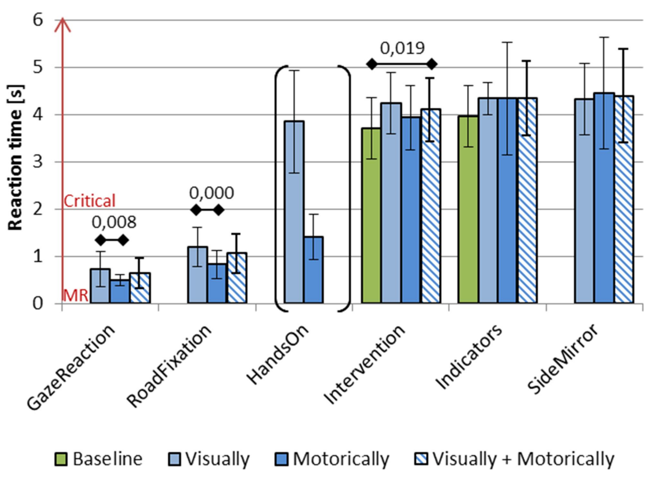

Figure 3: Reaction times of different subject groups

Unpaired t-test showed significant differences between the automation condition and baseline concerning the time of Intervention (p=0.019; r=0.319) and differences between the visual and motoric group concerning GazeReaction (p=0.008; r=0,361) and RoadFixation (p<0.001; r=0.473). Visually monitoring subjects intervene on average 0.3 seconds later (mean=4.24s; SD= 0.64s) than the motoric group (mean=3.94; SD=0.68s). This difference was not statistical significant (p=0.158; r=0.234).

B. Usage of Acceleration Potential

Crucial for the controllability of the system is not only the point in time when the driver starts to intervene, but also how well he performs the following maneuver. Figure 4 shows the maximum occurred usage of acceleration potential in the situations. There is no statistical difference between the visual and motoric group (p=0.503; r=0.129), but there is between the automation and baseline group (p=0.033; r=0.263). No significant differences between the groups can be stated concerning the maximum lateral accelerations occurring in the situations.

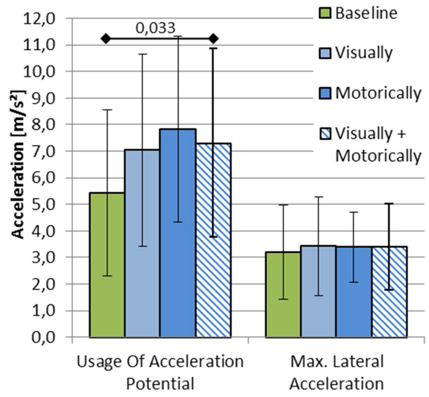

Figure 4: Usage of acceleration potential and lateral accelerations

C. Type of Intervention

Different distributions of intervention types can be observed between the groups. It can be distinguished between subjects not intervening, those braking and steering and those only steering. Braking only did not appear in any situation. When considering motorically and visually monitoring, the visual group seemed to be more unlikely to intervene and did not take over control in ten out of the 33 situations (30%), whereas in the motoric group, where subjects already had their hands on the steering wheel, only two out of 20 subjects did not intervene (10%) (Chi-squared test p=0.087). Concerning the baseline group, every subject reacted with a lane change and the brake was used less (See figure 5). Differences concerning the type of intervention between baseline and automated condition are significant with chi-squared test (p=0,017).

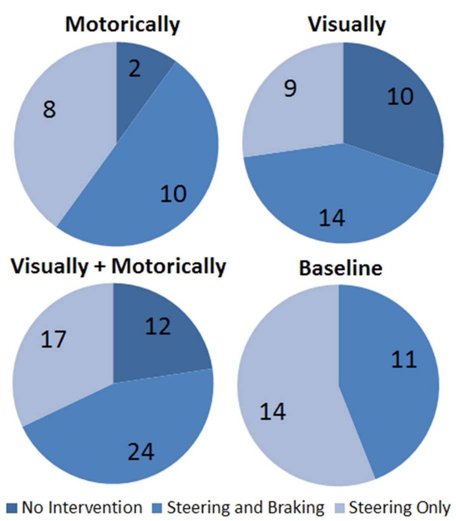

Figure 5: Types of intervention

D. *Subjective Rating*

The monitoring state is seen as rather advantageous. Subjects stated that it is comfortable and useful, even if it is not perceived as very safe (Compare Figure 6). Rather, they would prefer not to always get a complete take-over request ("Convential Take-over", see Figure 1) instead of the monitoring request.

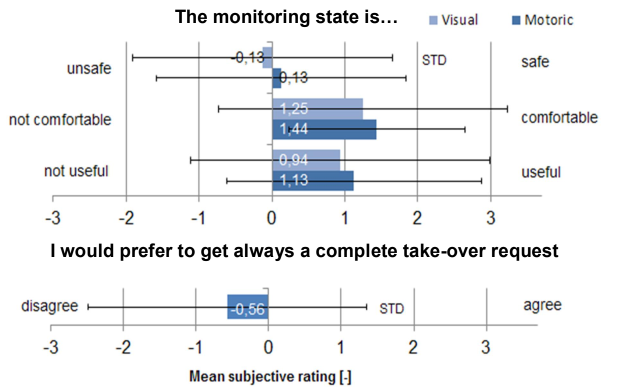

Figure 6: Subjective ratings

V. Discussion

The time and quality of intervention are essential for deciding whether prompting an MR is a safe method to handle system uncertainties. Following the results of Gold et al. [4], where 2.10 seconds intervention time for 5s TTB and 2.89 for 7s TTB have been measured, an intervention time of about 2.5 seconds could be expected for this study. Subjects intervened after 2.11 s (SD=0.67s) starting from the situation evolving into critical. A small improvement through two seconds monitoring is apparent, but at a cost of two additional seconds of required sensor range. Nevertheless, subjects driving without automation intervened 0.4 seconds earlier, after 1.70 seconds. Two seconds monitoring cannot compensate automation effects completely. Subjects intervene 0.3s if they monitor motorically after 1.94s and differences to the baseline are no longer significant ($p=0.261$; $r=0.187$). If subjects from the baseline would be considered who reacted before the situation evolved into critical, the baseline subjects would intervene significantly earlier ($p=0.020$; $r=0.329$) than the motorically monitoring subjects.

Concerning reaction times, a difference between the visual und motoric group in GazeReaction and RoadFixation was not expected. Nevertheless, subjects from the motoric group reacted faster to the MR. Perhaps the instruction to put the hands on the steering wheel produced higher urgencies than the instruction to monitor visually. The 0.3s faster intervention in the group of manual monitoring subjects corresponds to the time for the short physical hand movement to the steering wheel. It is expected that this difference would become significant with a larger sample.

The usage of the acceleration potential is higher in the automation group than in the baseline. Here too it becomes apparent that two seconds monitoring cannot compensate for automation effects. The difference originates from the fact that the brake is used more in the baseline condition, because there is no difference in lateral accelerations. This finding corresponds to Petermann and Schlag [6], who stated that the majority of the subjects brake as a first reaction to a transition request. In this manner subjects gain more time for the maneuver.

Several subjects (21%) of the baseline group did intervene before the situation evolved into critical and increased the safety distance to the situation. Although the situations are designed very critically and with a high probability to get involved in an accident, 30% of the visually monitoring subjects and 10% of the motoric group did not intervene at all. This matches the findings from Stanton and Young that "the presence of vehicle automation seemed to make drivers less likely to reclaim control in an emergency-braking scenario" [8]. A distinct automation effect that must be faced in future automated vehicles. Some subjects expected the automation to handle those critical situations without drivers' assistance. Of course, a future automation system would brake as the last choice. Nevertheless, the experiment was designed to measure reaction times and performance of the subjects. Automated systems, as they are implemented by humans and based on restricted resources, will never reach a 100% level and therefore, the driver remains an important fallback level, whose limits have to be well known.

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