"Take over!" How long does it take to get the driver back into the loop?

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Raising the automation level in cars is an imaginable scenario for the future in order to improve traffic safety. However, as long as there are situations that cannot be handled by the automation, the driver has to be enabled to take over the driving task in a safe manner. The focus of the current study is to understand at which point in time a driver's attention must be directed back to the driving task. To investigate this issue, an experiment was conducted in a dynamic driving simulator and two take-over times were examined and compared to manual driving. The conditions of the experiment were designed to examine the take-over process of inattentive drivers engaged in an interaction with a tablet computer. The results show distinct automation effects in both take-over conditions. With shorter take-over time, decision making and reactions are faster but generally worse in quality.

INTRODUCTION

In the past years an increasing number of active safety systems have been integrated in vehicles. Because of this development, highly automated driving is no longer just science fiction. Nowadays, Advanced Driver Assistance Systems (ADAS) are able to take over longitudinal (e.g. Adaptive Cruise Control) and lateral (e.g. Lane Keeping Assistant) guidance, or even both (e.g. Traffic Jam Assistant). As these systems are able to reduce the occurrence of human failures – which cause up to 90% of all accidents (Chiellino et al., 2007) – they have the potential to increase traffic safety. In addition, driver comfort can be enhanced by relieving him or her of the driving task. Primarily because automated driving is so advantageous, these systems are becoming more and more popular. Thus it can be said that the level of automation in modern vehicles is increasing and the role of the driver is about to change (Damböck et al. 2012b). By this means "driving safety increasingly depends on the combined performance of the human and automation" (Merat & Lee, 2012, p. 681). The role change leads to a change in the driver's behavior, depending on the level of automation (Flemisch et al., 2008; Peterman & Kiss, 2009) and the degree of involvement in the driving task. The development of automated cars mentioned above combined with the increasing number of nomadic devices will result in drivers that do not only withdraw their attention from the driving task but increasingly deal with other tasks while driving (Hancock et al., 1999). In the mid-term future, there will still be situations which the automation will not be able to handle (e.g. system boundaries). The availability of the driver will be one of the main issues. As long as such system boundaries exist, the driver is needed as a backup in case the automation has to redirect the driving task to the driver. It is fundamental that the driver is made aware of this transition early enough to avoid potentially dangerous situations and to ensure a comfortable take-over process (Damböck et al., 2012a). The time needed for take over depends on how long the driver needs to gather information from the environment and develop sufficient situation awareness (Endsley, 1995). Only after the driver has been able to comprehend the current scene, he or she is able to take over the driving task from the automation. Several different factors have an impact on this process, e.g. the complexity of the driving situation. In this context, automation effects known from aviation (Bainbridge, 1983; Endsley & Kiris, 1995; Sarter & Woods, 1995) are imported into the vehicle domain.

To improve usability and acceptance of automation systems, take-over times should aspire to allow safe and successful take-overs. Figure 1 shows the chronological sequence of a take-over process with a transition from highly-automated to manual driving. However, the available time is limited by the range of the system's sensors and their ability to predict system boundaries. Therefore, the time the driver needs for regaining control of the driving task is a very important issue for engineers dealing with maximum sensor range and allowed speed of the automation.

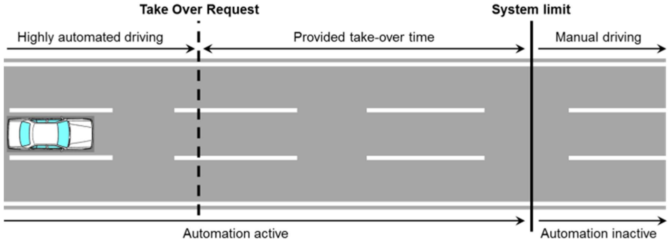

Figure 1: Schematic illustration of the sequence of a take-over process (Damböck et al., 2012a)

The question that has to be answered is as follows. At what point in time, prior to the occurrence of a system boundary, does the automation-system have to engage the attention of the driver in order to ensure a successful take-over process, even if the driver is out of the loop.

METHOD

In a high fidelity driving simulator of the BMW Group Research and Technology, 32 subjects went through a highly-automated driving scenario and had to react to a take-over request. A second group of 17 subjects went through the same scenario but without any assistance of the automation, to create reference values. A between-subject-design was chosen to prevent influences of learning effects.

Experimental setup and test subjects

Simulator. The high fidelity driving simulator consists of a motion based full vehicle mockup with a 180 degree field of view. The rear visibility by the side mirrors is realized by one projector for every mirror. A display right behind the vehicle's back seats provides an image for the rearview mirror. All relevant driving data including hands-on detection as well as 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 reactions from different angles. Moreover, the subjects wore a head mounted eye tracking system (Dikablis) to track their gaze behavior.

Subjects. The 32 subjects were employees of the BMW Group and between 19 and 57 years old (Mean=27.6; SD=8.7). 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. With a second group of 17 subjects, a baseline-study was conducted. Four of them had to be sorted out because of kinetosis and technical problems. The remaining 13 subjects, also BMW Group employees, were between 20 and 43 years old (Mean=27.4; SD=7.7) and consisted of 9 male (69%) and 4 female (31%) participants. Because the gaze behavior of manually driving subjects is not comparable to those driving highly-automated, the baseline-study group did not have to wear the eye-tracking system.

Secondary task. For the investigation of a worst case scenario, where the driver is out of the loop and not monitoring the system, a secondary task was provided. Therefore, the mainly visually demanding Surrogate Reference Task (SuRT; ISO/TS 14198) was implemented and extended by a score graph, to increase motivation and distraction of the subjects. The task was provided sequentially for 30 seconds with one minute of interruption in between and presented for one half of the subjects on a hand held nomadic device (tablet computer) and for the other in the center console.

Automation and system boundaries

Highly-automated driving is defined by Gasser et al. (2012) as a system which takes over longitudinal and lateral control for a specific period and in specific situations. The driver does not have to continuously monitor the system but if required, the system can request a take-over. The driver has to be given sufficient time for the take-over. Furthermore, system boundaries are reliably detected by the system.

The implemented automation fulfills all the requirements for a highly-automated vehicle. Besides longitudinal and lateral control the system was able to perform lane changes and overtake vehicles driving slower than the maximum speed of the automation (120 km/h). To ensure a high automation confidence and therefore an intense activity in the SuRT, the subjects were told that the system was flawless, that they could withdraw themselves completely from the driving task, and that the automation does not require their assistance or any monitoring unless it prompts a take-over request (TOR). Such a TOR is announced as soon as the vehicle reaches a system boundary of any kind. For this case the subjects were instructed to put the hands back on the steering wheel and take over control of the vehicle. The automation shuts off as soon as the driver steers or brakes. Additionally, there is a button on the steering wheel which can turn the system on and off. The TOR was provided acoustically (sinusoidal tone) as well as optically (icon in the instrument cluster), in order to enable a fast reaction.

Take-over scenario and experimental design

Test track. The subjects had to drive on a three-lane freeway with a hard shoulder. In a first familiarization drive, the subjects were able to drive manually, learn how to turn the automation on and off, and got familiar with the presentation of the TOR. In a second walkthrough (the actual test drive), the subjects had to drive highly-automated and deal with the secondary task. After a certain period of time, the automation prompted a TOR while the subject was engaged with the secondary task. The driving time prior to the TOR varied between subjects (mean=14:26 min; SD=2:27 min).

Take-over scenario. The take-over scenario due to the system boundary was represented by an accident on the right lane of a three-lane freeway. The driver had the option either to stop on his lane through a sudden emergency brake, or to swerve to the middle lane in order to avoid an accident. To make this second opportunity possible, the middle lane was not occupied by any other road user, but the subject still had to secure the lane change by mirrors and shoulder check. To be sure that a random glance at the scenery does not lead to a premature detection of the system boundary, a leading vehicle obscured the accident. At the same time the TOR was prompted, the leading vehicle suddenly swerved to the middle lane and uncovered the crashed vehicles.

Baseline-study. The baseline-study group had to drive the same track, but without any assistance of the automation. Also there was no warning sound when approaching the accident. The subjects were told to keep the same speed like in the test condition (120 km/h) and drive on the right lane whenever possible. In order to ensure that all drivers drove on the right lane when reaching the accident, a huge gap was inserted behind the obscuring leading vehicle. Thus comparable situations between manual and automated driving were established.

Independent Variable

The independent variable was the advance warning time (TOR-time) which is equivalent to the time to collision (TTC) at the moment of the TOR. For one half of the subjects the TOR arises 5 seconds before the accident, for the other half 7 seconds. By this measure, different TOR-times can be compared and the effect on driving performance can be investigated. In the baseline-study, the different TOR-times are achieved through the different point in time when the leading vehicle swerves to the middle-lane.

RESULTS

Before the results were extracted from the data, the data was reviewed. The eye tracking showed that the accident attracted the attention of four subjects whose reaction changes through an enhanced attention paid to the scenery. These subjects are not further considered in the analysis, which is why the total amount of subjects in the automated condition is reduced to 28: Thirteen subjects with a TOR-time of 7s and 15 with 5s (cf. Table 1). In our experimental setup the location of the secondary task had no significant influence on the dependent variables, wherefore it is not further considered.

Table 1: Subjects participated and considered

Condition	TOR	Participated	Considered
Automated	7s	16	13
	5s	16	15
Baseline	7s	9	8
	5s	8	5

Reaction type

The subjects can be distinguished by their reaction. Therefore, the subjects were divided into three groups. Figure 2 shows the distribution of the different reaction types of the two TOR-times. The reactions are changing with a different TOR-time in the main-study as well as in the baseline-study. The amount of steering maneuvers increases with a higher TOR-time and the amount of braking maneuvers decreases. Considering that the baseline-study could also represent a take-over with a very long TOR-time, this trend continues until no subject is forced to brake in this situation and 100 % are just steering around the obstacle.

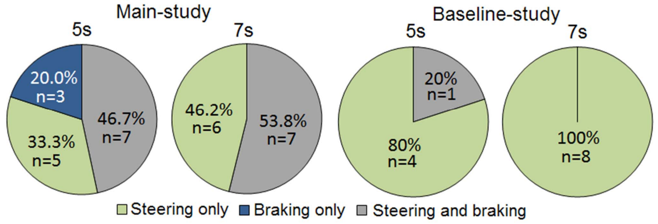

Figure 2: Reaction Types

Reaction time

Next to the type of the reaction, the point in time when the subjects start to brake or steer is essential. Therefore, the conscious maneuvers have to be distinguished from inputs at the brake or steering wheel, which are made unintentionally or only for the reason of vehicle stabilization. For this purpose, limits were defined from which an input is assumed to be a conscious maneuver. Regarding all relevant subjects, reasonable limits are 2 degrees steering wheel angle and 10 percent braking pedal position. Below those limits steering serves to stabilize the vehicle and the braking does not generate evident acceleration forces. By this definition, the mean times for braking input are 2.06 s (SD=0.34 s) for the 5s TOR-time and 3.10 s (SD=0.66 s) for the 7s group, starting from the TOR. Regarding the first conscious steering input, the mean time is 2.27 s (SD=0.66 s) for the 5s and 3.65 s (SD=1.33 s) for the 7s group. In summary, the first braking input comes approximately 1 second before the first steering input. With longer TOR-times the reactions generally occur later. A similar trend becomes apparent, when looking at the gaze behavior. Figure 3 shows the reaction procedure for the 5s and 7s group as well as the reaction times in the baseline-study. The times are mean values of the different groups.

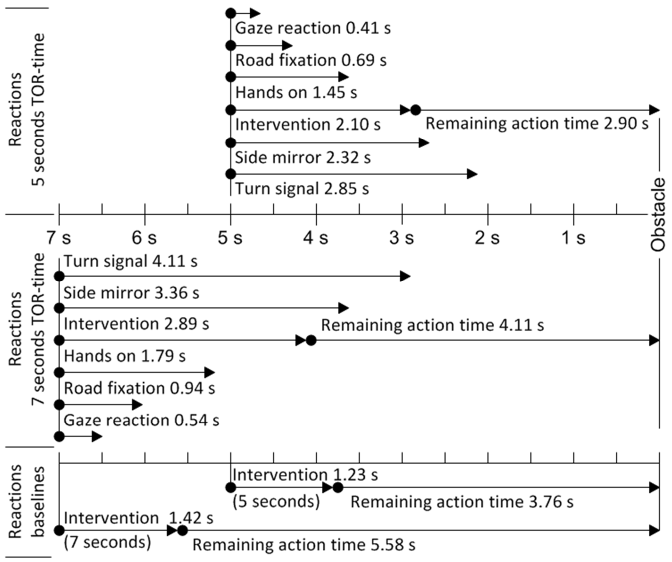

Figure 3: Reaction procedures

The "gaze reaction" is defined as the point in time when the first saccade stirs from the secondary task. "Road fixation" is the point in time when the first gaze at the scenery occurs. "Hands on" is the time from the TOR until the subject touches the steering wheel. The "intervention", is defined as the first conscious input, either braking or steering. The subject arrives at a decision and starts the maneuver. The remaining timeframe (TTC) to perform a lane change or brake until full stop is termed "remaining action time". "Side mirror" is the first gaze to the left side mirror, necessary to ensure a potential lane change. The "turn signal" tells the mean time until operation of the turn signal. Apparently all reaction times increase with a greater TOR-time. The remaining action time, however, also increases with TOR-time. In the baseline-study, one member of the 5s group intervened 3.7 seconds before the leading vehicle changed lane and uncovered the accident. This is why the intervention time gets close to zero (0.24 s; SD=2.25 s). Apparently the subject saw the situation before the leading vehicle swerved, or made the lane change accidentally. Both would justify the exclusion of the subject. If this outlier is not considered, the intervention time is 1.23 s (SD=0.5 s). Here too, the baseline-study differs obviously from both main-study conditions.

Trajectories

All trajectories from the four groups are shown in Figure 4, overlaid by a schematic illustration of the three-lane freeway. The vertical bold line at the zero-crossing symbolizes the system boundary. Trajectories of lane changes in the main-study are steeper than in the baseline-study. Furthermore, the different intervention-times become apparent. In the main-study with 5s TOR-time, two subjects used the hard shoulder and swerved to the right. In contrast, two subjects of the 7s baseline-study condition changed up to the left lane and increased the safety distance to a maximum, at cost of an additional lane change.

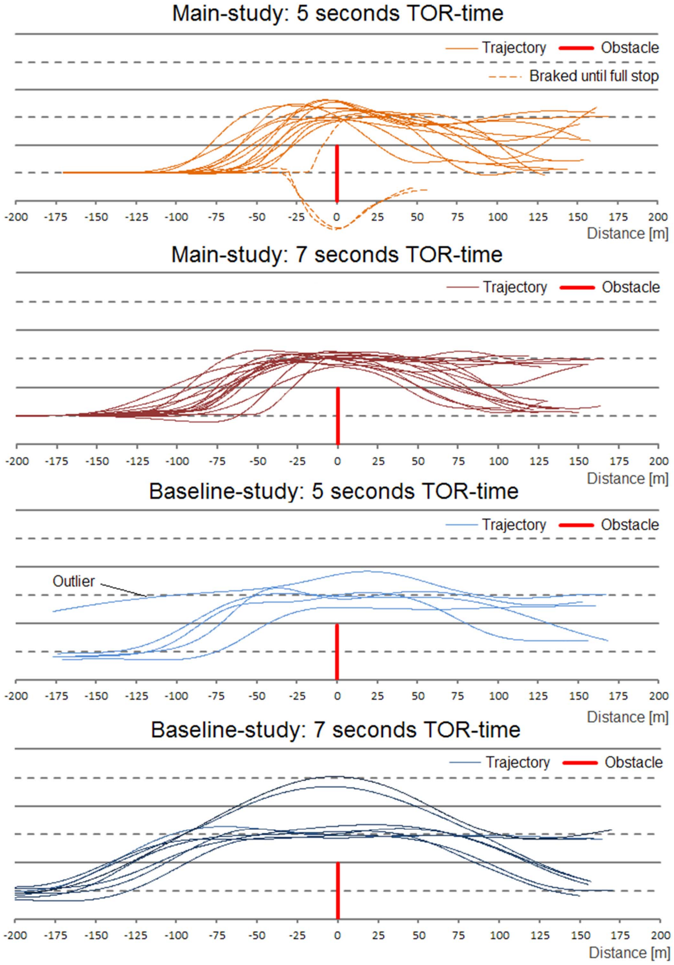

Figure 4: Trajectories

Securing lane change

Looking at the glances to the areas of interest while changing lanes and at the operation of the turn signal, Figure 5 shows the comparison of the two main-study groups. Only subjects which actually performed a lane change to the middle-lane are considered in the bar graph. In both groups, the side mirror and the indicator are used quite frequently.

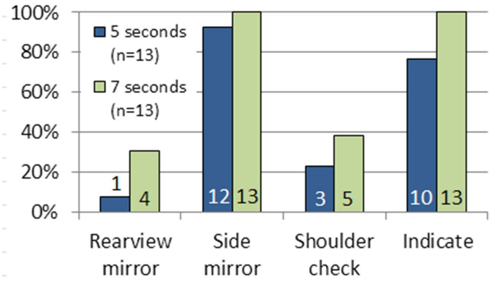

Figure 5: Lane change behavior

Only a few subjects used the rearview mirror, which is less important for the lane change. Whereas the look over the left shoulder to check the blind spot of the side mirror, the shoulder check, is much more relevant.

Acceleration potential

The driving maneuver can be assessed, depending on the accelerations that appeared during the take-over respectively the forces the tires had to transfer. If the acceleration approaches the physical limit, the driving condition becomes unstable. Therefore, the maximum acceleration which occurs after the TOR is a good measure for the quality of the reaction. Usually, the utilization of the maximum force that can be transferred between street and tire is determined by the circle of forces (Pacejka, 2006). As the weight of the vehicle and the friction coefficient remain constant in the simulation, a circle of acceleration can be defined (cf. Figure 6).

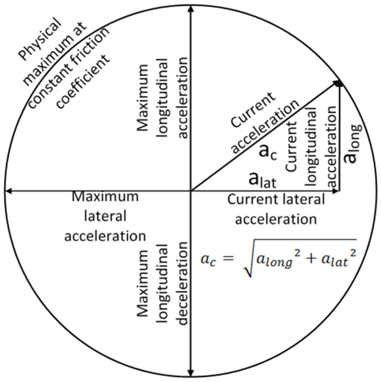

Figure 6: Circle of accelerations

By knowing the lateral (a_{lat}) and longitudinal accelerations (a_{long}) from the recorded data, the current utilization of the maximum acceleration potential can be calculated (a_c). Figure 7 shows the mean utilization of the acceleration potential. It has to be mentioned that all acceleration values are simulated and thus may differ from reality. The unpaired t test shows differences with a high effect size between the main-study and the baseline-study in the 5s TOR-time condition ($p=0.021$; $r=0.513$) as well as in the 7s condition ($p=0.013$; $r=0.534$). The difference between the two main-study groups is not significant ($p=0.419$; $r=0.0167$).

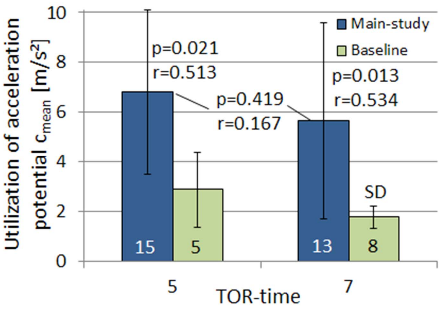

Figure 7: Utilization of acceleration potential

In the 5s condition, the main-study participants are generating mean accelerations (a_{mean}=6.81 m/s² ≈0.69 g; SD=3.29 m/s²), more than twice as high as the baseline-study group (a_{mean} =2.89 m/s² ≈0,29 g; SD=1.52 m/s²). In the 7s condition, the difference is even bigger and the participants of the main-study (a_{mean} =5.67 m/s² ≈0,58 g; SD=3.94 m/s²) are generating accelerations three times as high as the baseline-study group (a_{mean} =1.78 m/s² ≈0,18 g; SD=0.46 m/s²).

DISCUSSION

Looking at the reaction types, the more time the subjects have to come to a decision, the less they use brakes. This can be seen in the main-study as well as in the baseline-study group. The same effect appears when the TOR-time is kept constant and the situation awareness is increased by manual driving. If the driver has no sufficient time to make a lane change, or not enough situation awareness to come to a proper decision, the brake is used to reduce speed and to gain more time for decision making or performing the lane change. It can be stated that the usage of the brake suggests an insufficient timeframe for the reaction. This is the case in the majority of the 5s as well as the 7s condition of the main-study. In the 5s group the excessive demand of three subjects, deriving from the insufficient timeframe, results in unnecessary full stops and swerves to the hard shoulder. Furthermore, the longer the timeframe, the later the subjects react. This effect shows up in the main-study and in the baseline-study. The increase in situation awareness and attention of the drivers in the baseline-study results in an approximately half as long reaction time. This is expected to intensify if an acoustical warning should be presented as well in the baseline-study group. For example, Lee et al. (2002) found, that an acoustical warning significantly shortens the braking time of drivers, whether they are distracted or not.

The time gain of two seconds is divided and used for decision making as well as for the actual maneuver. Besides, the trajectories show that the subjects are using the additional time for increasing the safety distance and start the lane change earlier. The success of a lane change must not only be measured by derived parameters of the trajectories, but also by checking whether the driver is aware of the road scene and if he is sure that the target lane is not occupied by another road user. Because the driver is out of the loop in the main-study, we can assume that he doesn't know anything about other road users, especially not about the road scene behind him, when the TOR is prompted. In the 5s and in the 7s group a minor part of the subjects checked the blind spot by turning and looking over their shoulder. Would there have been a vehicle in the blind spot of the subject, accidents could have occurred in both main-study groups. Regarding the baseline-study, the awareness of possible vehicles in the blind spot cannot be judged. Another lane change quality characteristic is the utilization of the acceleration potential. Although the remaining action time of the 7s main-study group exceeds the 5s baseline-study group, the accelerations are higher and by this means the lane change riskier. The two additional seconds cannot completely compensate for the transition and the situational orientation of the subject, which is coming from out of the loop.

SUMMARY

The results indicate different manifestations of automation effects. With shorter TOR-time, the subjects come to a decision more quickly, reacting faster, but the quality is generally worse. With a decrease of the TOR-time the gazes in mirrors and shoulder checks decrease, the accelerations increase, and the brake is used excessively. If other road users had been in the blind spot, the risk of a collision would have been high. Compared to the baseline-study, the main-study subjects perform more poorly. They generate accelerations twice to three times as high as the baseline-study group and perform much more sudden braking maneuvers, unnecessarily endangering following vehicles. Under these experimental conditions, with a complete distraction of the driver, automation effects are still observable with a 7s TOR-time. The impact of these automation effects on a safe take-over have to be further investigated.

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