Investigation of Take-Over Performance of Driving Tasks by the Driver due to System Failure of Semi-Automated and Assisted Driving

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In the last decade a great variety of electronic systems have been developed which relieve the driver by automating primary driving tasks, mainly in order to improve overall safety and comfort. The driving tasks are thus split between the driver and the automation. A prerequisite for safe cooperation between driver and the automated system is that the driver recognizes when to take over control and begins to execute the tasks reliably which were previously performed by the automation. In this study the driver’s take-over performance of driving tasks of semi-automated and assisted driving is investigated on a test track in order to quantify the take-over-time depending on influencing variables such as the degree of automation or the task that has been taken over.

Practitioner Summary: Within this article two methods are derived and applied in two test-track studies in order to determine driver's take-over-time in case of system failure. Take-over-times are determined for the automation grades assisted and semi-automated after erroneous braking, acceleration and steering interventions.

Keywords: take-over-time, semi-automated-driving, driver-assistance-system, test-track-study

1. Introduction

In the last decade a great variety of electronic systems have been developed which relieve the driver by automating primary driving tasks, mainly in order to improve overall safety and comfort. The driving tasks are thus split between the driver and the automation, depending on the degree of automation (which reaches from assisted to fully automated driving, cf. Gasser 2012) and the configuration of the system. Nevertheless the driver is considered as a fall-back level that supervises the automation and takes over control if the automation fails to perform its tasks correctly. This requires that s/he realizes the necessity to act and performs the right actions to take over the tasks that were previously performed by the system.

This article addresses the driver’s take-over-performance of driving tasks of semi-automated and assisted driving. Assisted driving means that the driver operates the vehicle until a certain situation arises in which the assistance system takes over control for a short time (i.e. in order to avoid an obstacle). Afterwards it hands the driving tasks back to the driver. When driving in semi-automated mode, the automation performs the primary driving tasks such as longitudinal or lateral guidance; however, the driver must monitor the system and take back control if necessary (i.e. in case of a system failure). The reason for take-over actions can be manifold. take-over situations due to a system failure are assumed to be the most critical, because these situations occur unexpectedly, usually leaving no time for prior warning.

In order to assess the safety of the driver-vehicle system in cases of a system failure, criteria are needed to quantify the driver's take-over-performance depending on influencing factors, such as the grade of automation, the task that has to be taken over, the human machine interface, the traffic situation, etc.

In this study the driver’s take-over performance of driving tasks of semi-automated and assisted driving is investigated on a test track in order to quantify the take-over-time depending on influencing variables such as the degree of automation or the task that has been taken over.

In order to compare take-over-performance between different scenarios and grades of automation an evaluation method is needed that complies with the following requirements:

- works with all driving tasks taken over (i.e. lateral and longitudinal control)
- works in a high number of use cases
- applicable on test-track studies
- works for all degrees of automation
Hence in chapter 2 state-of-science methods to investigate take-over- and driving-performance are described. As no existing method complies with the previous requirements a new method is derived in chapter 3.1. In chapter 3.2 the experimental setup is explained. In 3.3 the method is evaluated by driving tests and driver’s take-over-performance in different traffic situations and grades of automation are assessed. The methodology and the results are finally discussed in chapter 4.

2. Related Work

In the following methods that were used in studies investigating situations in which drivers take-over driving tasks that were previously performed by the automation or react to system failure, are described.

Bender (2008), Fuchs and Abendroth (2008) as well as Fecher et al. (2009) investigated situations in which the driver principally guides the vehicle but an assistance system takes over longitudinal or lateral control for a short time. Bender (2008) analyzed the driver’s reactions after automated brake and steer interventions by observing the pedal and steering wheel position, the gaze behavior and the maximal position deviation from the optimal path. The take-over-time wasn’t assessed. Fuchs and Abendroth (2008) as well as Fecher et al. (2009) measured the muscular activity, the heart rate and the skin conductance and also applied eye tracking analysis and questionnaires to the test subjects to assess brake interventions that were caused by both, an unexpected object on the track and by a simulated system failure. They did not focus on the driver’s take-over-performance either.

In other studies the driver’s reactions to system failure of the vehicle’s lateral guidance were assessed. Neukum and Krüger (2003) investigated driver’s reactions to failures of a steering system. The standard deviation of the steering wheel angle, the maximum value of the yaw speed and the duration of the first and second steering movement after the failure occurred, were used as evaluation criterions for the criticality. Neukum (2009) tested the driver’s reaction to abrupt changes of the steering torque during different driving patterns and investigated the maximum yaw rate, the maximum needed track width and the duration until the maximum values were reached. In a study of Simmermacher (2013) the test subjects experienced a sudden disturbance of the lateral control during different driving tasks. The deviation from the optimal path and crossings with the lane markings were considered as a measurement for the driving performance.

Following studies investigating driver’s reaction to system failure or transition between automation grades using a system that automated at least one primary driving task. As part of a simulator study from Rudin-Brown and Parker (2004) the test subjects had to survey the traffic during an assisted drive and execute a secondary task at the same time. The authors measured the time between the lead vehicle’s break lights becoming visible and the event of the first reaction of the driver during automation shortfalls. They used the standard deviation of the lateral position to assess the driver’s performance of the lateral control. Carsten et al. (2012) tracked the eye movement and observed the heart rate of test subjects during transitions of assisted rides on different automation grades. In a similar study Stanton (1997) observed whether drivers steer, steer and brake or crash into another car in case of a failure. Petermann and Kiss (2009) focused on the transitions between four different levels of automation. A change to a higher level of automation was announced and the test subjects were supposed to press a button as soon as they were ready to take over the control. The time between the appearance of the take-over request and the push of the button was considered as a reaction time. In the case of taking over the full control of the car the reaction time until the first movement of the steering wheel occurred, was measured after a deer appeared on the street. Nilsson et al. (2013) used the minimum time-to-collision (TTC) and the time-to-headway (TTHW) relative to a preceding vehicle in order to quantify the takeover after an erroneous acceleration, an insufficient break maneuver, a complete malfunction during a rear-end collision situation and a disregard of the speed limit by an ACC-system. Strand et al. (2014) varied the brake force in a critical situation between 0 and 60 percent of the necessary level for preventing a crash during a ride either with longitudinal or with longitudinal and lateral assistance. TTC, TTHW, the time between the beginning of braking of the preceding vehicle and the beginning of pressing the brake pedal were observed. Buld and Krüger (2002) used TTC and standard deviation of the lane position within a similar study as well as Waard (1999) who applied an electrocardiogram and measured the time between another vehicle beginning to merge into the driver’s lane and the first use of the brake in order to investigate the transition of automation modes caused by failures within highly automated systems. Bloomfield et al. (1995) and Bloomfield (1998) surveyed the lane and velocity keeping quality after a longer ride with a highly automated assistance system by measuring the standard deviation of the steering wheel angle, the number of zero crossings of the steering wheel position.
and reaction times regarding gaze reaction, hand reaction and intervention times without focusing on the take-over procedure. Gold et al. (2013a) analyzed the benefit of a semi-automated backup level for highly automated cars by comparing the results of a transition to manual drive either executed in one or two steps. Reaction times, eye motion analysis and questionnaires served as methods for the ascertainment of the quality of the transition. Gold et al. (2013b) applied the same scenarios and, in addition varied the time-to-collision for a potential crash that would occur with a preceding vehicle without take-over-reaction after handing over the control to the driver. By analyzing the eye movement and the time between a person entering the street and the first related steering wheel or pedal movement, they were able to determine the time for a take-over action in that very specific case. Damböck and Bengler (2012) used a similar methodology for a highly automated system. They conducted a simulator study with three different critical driving situations and they varied the time-to-collision with the road marking in order to identify a minimum duration for the transition. If a pass-over became unavoidable the minimum time for the transition was reached.

The evaluation criteria used so far, are inappropriate in terms of our requirements mentioned in chapter 1. Reaction time from the take-over need until the first reaction of the driver is not applicable to the assessment of the take-over procedure that takes place after the first reaction. The deviation from the optimal path requires the definition of an optimal path, which is not possible within the most driving patterns as there is not a single optimal path. Physiological conditions, eye tracking and questionnaires are subjectively measurable and complement an objective assessment. The standard deviation of steering wheel angle, lateral position and velocity as well as the number of zero crossings are only considering either lateral or longitudinal control. So it is not possible to compare take-over-time with these measurements. Signaling the readiness of taking over the control by pressing a button is inappropriate for investigating automatic interventions and failures. Maximum deviations i.e. of the yaw rate, steering wheel angle, lateral and longitudinal position as well as acceleration and measurable speed do not make it possible to compare take-over-performance between system failure of lateral and longitudinal control. TTC and TTHW are only usable in situations with a reference point. Moreover the calculation of take-over duration by the variation of the TTC is unsuitable because it is not appropriate to vary the TTC in the same situation for the same subject several times in order to figure out which time is necessary to avoid a collision due to the built up expectations of the test subject.

The mean lateral position and the time to lane crossing (Östlund et al. 2005 and Reichart 2001) are, like the high frequency steering rate and the steering wheel reversal rate, only applicable for assessing the control during long-term drives. The investigation of typically short take-over performances requires a method which is able to quantify the impact of system failures and make different scenarios comparable. Hence we had to discover a method that enables the calculation of a take-over-time regardless of degree of automation, task taken over (longitudinal or lateral control) and other specific variables. A crucial determinant for the safety of take-over tasks is the duration between the end of the performance of a driving task by the automation and the regained lateral and longitudinal control, what hasn’t been defined so far. We identified the normalization of measurements that describe the longitudinal as well as the lateral vehicle dynamics (such as the vehicle’s longitudinal and lateral acceleration, the velocity, the steering wheel angle, the yaw angle and the lateral distance to the lane markers) as the point of time which displays the end of a transition. The method is described within the next chapter.

3. Evaluation

3.1 Quantifying take-over-performance

To determine the driver’s individual take-over-time it is necessary to find appropriate procedures and criteria to determine the beginning and end of the take-over-procedure. The first regulatory activity by the driver, such as the operation of a human-machine-interface like the steering wheel, accelerator or brake pedal can be seen as the beginning of the take-over. After the driver has initiated the take-over-procedure, a certain period of time passes until s/he has corrected the faulty intervention and the vehicle is under his/her control. In order to bring the vehicle under control, the driver has to convert it into a safe state. For this reason, the take-over is seen as completed as soon as the driver has controlled the vehicle and is driving straight ahead within the lane and has a constant speed, corresponding to the driving task. To identify this time, two methods are proposed. These are:
• Method A: Normalization of the measured value
• Method B: Normalization of the standard deviation of the measured value

These methods use the mean and standard deviation of vehicle dynamics value to determine the end of the take-over by the driver. Possible values are the vehicle’s longitudinal and lateral acceleration, the velocity, the steering wheel angle, the yaw angle and the lateral distance to the lane markers. These values can be measured by in-vehicle devices of state-of-technology advanced driver assistance systems (ADAS). Both methods will be presented below and their advantages and disadvantages will be discussed.

Method A: Normalization of the measured value

In this method, first the standard deviation (σ_ref) of a measured value (i.e. steering wheel angle) is determined during a defined time span (here 50 s, figure 1) based on a reference measurement on a straight track. The take-over of a driving task by the driver is considered as successfully completed when the measured value first enters the confidence interval \( \mu_{\text{ref}} \pm 2 \times \sigma_{\text{ref}} \) (\( \mu_{\text{ref}} \) representing the mean value of the reference measurement) and stays inside the interval for at least 1 s. The confidence interval includes 95.4% of all values of the reference measurement. The time span of 1 s is chosen according to Donges (2012) as the anticipation time in the stabilization layer is about one second. If the measured value reenters the 95.4% confidence interval and remains there for at least one second, it can be assumed that the driver had anticipated that no further stabilization is necessary and thus the vehicle is under his full control. Figure 1 shows the reference measurement and figure 2 the measurement after an automatic intervention on the right side. The red markings represent the 95.4% confidence interval.

Method B: Normalization of the standard deviation of the measured value

In this method, the take-over is considered as successfully completed when the amount of fluctuation has normalized to the level of a reference measurement (driving straight ahead at a constant speed). For this purpose, the observation is not focused on the measured value itself but the standard deviation of the measured value which represents the fluctuation. Afterwards the standard deviations for a given interval \( t_x \) are calculated on a rolling basis. This means that with each new value in the measurement there is a calculation of the standard deviation for the interval \( t_x \). This calculation is performed for the entire reference measurement. The result of this calculation is a set of standard deviations of the interval length \( t_x \). An interval length \( t_x \) of four seconds is chosen, according to Simmermacher (2013), Damböck & Bengler (2012) and Wallentowitz et al. (2002). Wallentowitz et al. (2002) showed that corrective actions by the driver in the
steering system disorders were leveled out after four seconds. According to Damböck & Bengler (2012) disturbances are compensated on to a stabilization level after 4 seconds. Simmermacher (2013) uses this information and examines the driver’s reaction in evasive maneuvers and braking interventions for a time period of four seconds. Afterwards the mean value is calculated and thus a 95.4% confidence interval is formed. Once the standard deviation of the measured value after the automatic intervention enters this confidence interval and remains there for 1s (as in method A), the take-over is seen as successfully completed.

Both methods have the goal to calculate the individual take-over time. Method A has the advantage that the take-over time is only dependent on the period of time that the measured value has to remain within the confidence interval. However, this method can only be applied when there is a target value for the measured value. If there is no target value, either the confidence interval becomes very large and has therefore no meaning or the measured value normalizes in a different area and as such the confidence interval is not entered. As an example the lane position can be taken. Here no concrete target position while driving in the lane exists. If there is an automatic intervention such as a momentum which causes the car to drift to the left the driver will stabilize the vehicle, but even if he keeps driving straight ahead, he must not necessarily have the same position as before. In such a case method A cannot be used.

Method B, however, can also be applied to variables that do not have a target value since it observes the fluctuation. The disadvantage, however, is that the take-over time is dependent on two values. Firstly the interval length \( t_x \) and the period of time that the measured value has to remain within the confidence interval. In the following chapter both methods will be assessed in driving tests.

### 3.2 Experimental setup

In order to determine take-over-times and to evaluate the described methods two studies were conducted on a test track. The test vehicle was a modified VW Passat B7 with automatic transmission. The vehicle’s surroundings were detected via several on-board radar sensors and a stereo camera and processed by software (Bauer et al. 2015; Cieler et al. 2014), which gives orders to steering and longitudinal guiding actuators. Vehicle dynamics data was recorded during the experiments. The evaluation was conducted on a straight test track of 1.1km length.

In the first study \((n = 46\) subjects, age \(M = 40.5, SD = 17.3, 17\) female) the degree of automation was assisted, which means that the driver performs all driving tasks, but the system intervenes in certain situations. In the second study \((n = 32\) subjects, age \(M = 33.4, SD = 12.9, 7\) female) the grade of automation
was *semi-automated*, which means that the automated system performs the longitudinal and lateral guidance as well as lane changes; the driver delegates maneuvers to the system, supervises it and intervenes if necessary. The subjects were requested to maintain a speed of 30 km/h, follow the lane and keep the hands on the steering wheel. In the first study (assisted) following four system interventions occurred.

**Steering:** A torque of 5.5 Nm was applied on the steering wheel for 0.25 s.

**Steering with obstacle:** A torque of 5.5 Nm was applied on the steering wheel for 0.25 s, when a box-shaped obstacle approached the vehicle from the right.

**Acceleration:** An acceleration of 1.2 m/s² was applied to increase speed from 30 km/h to 40 km/h.

**Deceleration:** A deceleration of 2.2 m/s² was applied to reduce speed from 30 km/h to 20 km/h.

The situations *steering*, *acceleration* and *deceleration* represented interventions due to system error, the situation *steering with obstacle* an automatic avoidance of a critical obstacle. In the second study (semi-automated) all interventions except for *steering with obstacle* were performed identical to study 1. After the system interventions the driver had to take-over the longitudinal or the lateral guidance in order to fulfill the driving task.

### 3.3 Results

Figure 5 shows take-over times in study 1 (assisted) determined with both methods. In the situations *steering* and *acceleration* method A finds higher take-over-times than method B. In the situation *deceleration* it is the other way around. In the situation *steering* the mean take-over-times are shorter than in situations *acceleration* and *deceleration*. The reason for that could be that in the situation of *steering* the driver gets direct feedback about the system intervention as s/he holds his/her hands on the steering wheel. Furthermore the situation is more time critical than acceleration and deceleration because the vehicle would leave the road without an intervention by the driver.

![Graph showing take-over times](image)

**Figure 5.** Take-over-times in study 1 (assisted) determined with method A and method B, n=46

In Figure 6 take-over times determined in experiment 1 (assisted) and experiment 2 (semi-automated) using method A are shown. In situation *steering* a significant difference between assisted and semi-automated cannot be determined. In the situations *acceleration* as well as *deceleration* the take-over-time of the automation grade *semi-automated* is significantly higher than in the automation grade *assisted* (unpaired t-test, significance level p<0.05). In situation *accelerating* the mean take-over-time in the automation grade *semi-automated* is 1.7 times higher than in automation grade *assisted*. In the situation *decelerating* the factor is even to 3.9. The reason for this could be that the driver, in the situation of *steering* recognizes the system error early in both automation grades as s/he holds the hands on the steering wheel. The reason for the high difference in the situations *acceleration* and *deceleration* could be explained that the driver retracts
him/herself from the vehicle guidance and/or does not feel the need to intervene as the situation’s criticality is perceived as low.

Figure 6. Take-over-times in study 1 (assisted, n = 46) and study 2 (semi-automated, n = 32) determined using Method A

4. Discussion

Results show that both methods are feasible in order to determine take-over-times in take-over situations in different use cases for the automation grades “assisted” and “semi-automated” on a test track. Method B has an advantage over Method A in respect that it can also be applied to values whose desired values cannot be exactly named, which is for example the case for the distance to lane markers. Both presented methods can be helpful in order to assess controllability of system failure of automated systems. The advantage over measurands as the TTC is that they can quantify the whole take-over process and also work without a reference point. Nevertheless both methods were only tested on straight tracks. Is has to be assessed if they also work on road bends and in more complex traffic scenarios. It should also be verified that the assumption that the take-over process is over when the measured value stays within the confidence interval for one second. Furthermore the length of interval $t_3$ of Method B should be verified.

It could be shown that a strong prolongation of take-over-time in the automation level semi-automated in comparison to assisted in the situations “accelerating” and “decelerating” takes place. It should be further investigated how a take-over-request via the human-machine-interface could influence the take-over-time.

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