Earth, Life & Social Sciences
Kampweg 5
3769 DE Soesterberg
P.O. Box 23
3769 ZG Soesterberg
The Netherlands

www.tno.nl

T +31 88 866 15 00
F +31 34 635 39 77

TNO report

TNO 2016 R11589

Adaptive Virtual Tow Bar and Transition of Control: A truck driving simulator study

Date	November 2016
Author(s)	Dr. E.S. Wilschut Ir. D.M.C. Willemsen Ir. J.H. Hogema Prof. Dr. M.H. Martens
Number of pages	55 (incl. appendices)
Number of appendices	3
Project name	ERP HE Adaptive Automotive Automotion
Project number	060.21023

Summary

Background: Truck platooning, with trucks being virtually connected, is getting more and more attention. Truck platooning offers the potential for substantial fuel savings while allowing the truck driver in the platoon to take a rest. However, at the current state of technology, truck drivers are still required to be alert and ready to intervene if required. How safe this situation of platooning is depends partly on whether the driver is able to take over control when requested. Under normal conditions, a transition back to the driver is requested by the system and the truck driver is provided with sufficient time and the situation is not too time critical. Under other conditions, a driver may need to respond to other traffic soon after taking over control, for instance by means of braking. Quite some studies have been performed about transitions of control from automated to manual driving, however studies with professional truck drivers in various platooning situations are scarce.

Objective: The aim of this study was to investigate how long it takes before truck drivers take back manual control after a system warning if they can choose their own moment of getting back control.

Methods: We studied various scenarios, in which drivers either had to monitor the surroundings, work with a tablet or keep their eyes closed. Besides the response times, we also studied the quality of the driving behaviour right after taking back control in order to investigate whether drivers were actually ready to take back control in normal conditions and also in conditions in which they needed to brake as a response to a braking lead vehicle. 22 professional truck drivers took part in a truck driving simulator experiment. An automated motorway truck platooning system was simulated that allowed the participant to hook on to a lead truck and follow automatically at close distance with hands off the steering wheel and feet off the pedals. All participants made 9 drives, including a manual truck driving condition to get a baseline condition. After hooking on to the platoon, they drove in automated platooning mode until the system requested them to take back control. After getting a warning, they could press a button on the steering wheel to indicate that were ready after which they got back control. Response times were recorded, as well as the quality of driving behaviour after the transition and responses to a lead vehicle braking action. Also, situational awareness and acceptance were studied, as well as eye movements, feet, hand and body position as well as input from wearables measuring heart beat and arm movements.

Results: In case of voluntary take-overs, with truck drivers choosing their own moment to take back control after being requested by the system, response times vary quite substantially per condition and per driver. When drivers were asked to monitor the surroundings while platooning, mean response times were around 2.5 seconds, with not so much variance between drivers. For the condition in which drivers were working with a tablet, these response times doubled to around 5.5 seconds, with increasing variance. For the condition in which drivers had their eyes closed, mean response times were a little over 6 seconds, with a large variance and the slowest response times being over 16 seconds. When drivers had been platooning with shorter headways, they took somewhat more time to take back control.

After having taken back control, the driving performance was measured and compared to manual truck driving behaviour. Under normal driving conditions, we found that overall performance was comparable to their normal driving behaviour. However for the condition in which drivers had been working with a tablet, there seems to be some negative after-effect of platooning on lateral performance, although effects are relatively small and seem to disappear over time. In the conditions in which drivers have to respond to a braking lead truck after taking back control, we see adequate responses to the lead truck although the minimum time to collision is sometimes quite low. The wearables did not deliver reliable results since there was a very low correlation between the two wrist bands that were used. Automatic analyses of eye movement data, hand, feet and body position showed to be quite complex due to the fact that drivers sometimes obstructed the video images with body or arms, and that sometimes short glances were done to the road that were not automatically detected by the Smart Eye camera. In general, participants were rather positive about the system, with a score of 7 out of 10. The majority of drivers would like to have this system in their truck, even though the trust of the system in the simulator was higher than their trust if they imagined using this on the real road.

Conclusion: Drivers that were instructed to monitor the surroundings while truck platooning have short take-over times and lower variability in response times than drivers using a tablet or having their eyes closed during platooning. Remember that in this study, drivers could indicate themselves whether they were ready to take back control, so they could take more or less time. Drivers take more time to get back control when they have been platooning at shorter headways. Apparently truck drivers are aware that they had been out of the loop for a while and are aware of the involved risk in short following distances. There were large individual differences in response times between drivers, with large differences within one condition between drivers, but also with large differences between the different conditions. The large variability in response times is probably also due to the individual differences in body, hand and feet position, and in the fact that people were holding a tablet, were sometimes wearing reading glasses or changed the seating position of their chair. This is behaviour we could see on the video images, and more detailed analyses of the video images will be done in order to find further explanatory variables for differences in response times.

Contents

1 Introduction

This document reports a truck driving simulator study that was performed as part of the Early Research Program (ERP) Human Enhancement: A*daptive Automation.*

First, background information is provided about the Early Research Program and the Adaptive Automotive Automation part of the ERP and the use case ‘Adaptive Virtual Tow Bar (A-VTB)’ is explained in more detail. The main part of the report is the presentation of the method and results of the truck driving simulator study that was performed in 2015.

1.1 Early Research Program: Human Enhancement

In the industrial and mobility sector an increase in the level of automation of functions is taking place in order to increase the efficiency and avoid human error. An example of this increasing level of automation in the mobility domain is ‘automated driving’. Although a lot of attention is being paid to the technological developments and sensors, the actual behaviour and interaction of users with these systems is the key to successful innovation. If technological systems are designed as a joint cognitive system, working together with the human, optimized human-system interaction will result.

The first ambition of the large scale TNO Early Research Program (ERP) Human Enhancement is to develop a transparent (human-in-the-loop) adaptive automation platform that substantially improves safety for manoeuvring and control tasks, based on a computational human model to assess current and predicted human task load. Within the programme Human Enhancement, Adaptive Automation is one of the main foci. In Adaptive Automation, the idea is that the control of systems shifts between humans and machines dynamically, depending on environmental factors, operator workload, and performance. The control may shift because of limitations in the automated system, due to system failures, system boundaries or because the human and/or the combination human/system can perform better than the automated system by itself.

There are two projects in the ERP, namely a maritime and offshore project and an automotive project. The results described in this report were generated for the automotive project, and in particular for the A-VTB use case which will be described later in the report.

1.2 Adaptive Automotive Automation

In the Adaptive Automotive Automation project the focus lies on driving automation that helps people to drive safer, more efficiently (using less fuel, causing less congestion), more comfortably etc. Driver support and automation of driving tasks (up to highly automated driving) are a major trend, with the first functions being introduced for comfort such as cruise control and adaptive cruise control (ACC). However, also active safety functions like Autonomous Emergency Braking Systems (AEBS), Lane Departure Warning Systems and Collision Avoidance systems are now commercially available. Currently, trends lead towards more and more extensive automated driving, but they work the same for all drivers.

Some elements do have settings a driver may adjust themselves, although in most cases, drivers do not use these options and the types of things a driver can choose are very limited. At this moment, automated systems primarily work well on motorways, but even there the technology that is commercially available is not yet reliable enough to take the driver completely out of the loop and transfer him or her temporarily into a passenger rather than a driver. The role of the driver in the currently available systems is clearly changing from being in full control (manual driving with or without driver support) towards supervising automated processes with limitations. The foreseeable future is that the driver may be able to be temporarily out of the loop, being a passenger in a highly automated vehicle, but needing to take back control when the vehicle requests this. The consequences for the driver in his changing task are substantial: the boundaries of the operational tasks may be unclear, the attentiveness towards his operational responsibility may reduce as the vehicle takes over, while still having the formal responsibility for safe driving. This may result in the driver getting out of the loop and confronted with automation surprises or lack of situational awareness once he/she needs to take back control. The main question that is currently being asked is: How long does it take for a driver to get back control? However TNO firmly believes that there is not a single answer to this question. We believe that this at least depends on the type of driver, the type of function he as (monitor or being allowed to be out of the loop) and the type of activities a driver performs while being out of the loop. We therefore believe in an adaptive approach, in which we, based on several parameters that have yet to be determined in studies, are able to predict how long it will take before a driver will take back control, and how well he/she is prepared for performing the driver task again.

1.3 Adaptive Virtual Tow Bar

The use case of the Adaptive Virtual Tow Bar (A-VTB) describes a truck platooning situation in which two trucks are virtually connected through a communication channel (also referred to as ‘platooning’). The first truck is a truck that is manually driven by a professional truck driver (level 0 in the SAE definition of automated driving: manual driving), possibly assisted with driver support systems like ACC and LKA (SAE level 1: driver support systems). The second truck is driving behind the first truck in highly automated mode, using information gathered by means of cooperative technology and its own sensors. Because of the cooperative technology in both trucks, they can drive with a small time gap between the trucks and thereby save fuel due to better aerodynamics. Besides that, the driver of the second, automated, truck will be temporarily out of the loop, being able to relax or maybe do additional tasks. Truck platooning is currently under development by TNO together with truck companies and freight companies, and the Dutch ministry is stimulating this development in order to be able to actually get this on the road whenever a safe situation can be offered. In 2016, the European Truck Platooning Challenge was organised in the Netherlands in order to stimulate the truck platooning developments. However, the technology is not yet commercially available and still under development.

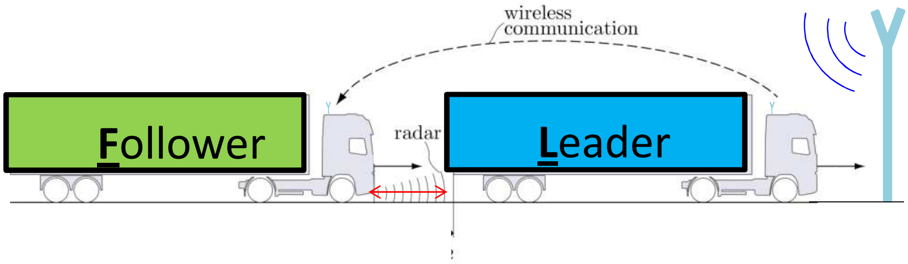


Figure 1.1 Virtual Tow Bar with first vehicle (Leader) and Follower.

Due to the fact that the trucks are following at a close distance, it cannot be expected from the driver that he is still monitoring the surroundings and the driving task, since he cannot see the traffic in front (due to driving closely behind a high truck). This may also have consequences when the second truck driver needs to take back control. This means that the VTB system will be an SAE level 4 system: the steering, acceleration/deceleration of the vehicle, the monitoring of the driving environment is performed by the system and the driver is not seen as a fall back option of the dynamic driving task in case of a sudden system failure. The system failure also has to be solved by the system (hence the driver can temporarily be fully out of the loop).
For the VTB system different transitions of control can take place. The normal way of using the system, i.e. without failures and assuming usage is only allowed on dedicated rural roads or motorways, is given in the figure below (Figure 1.2):

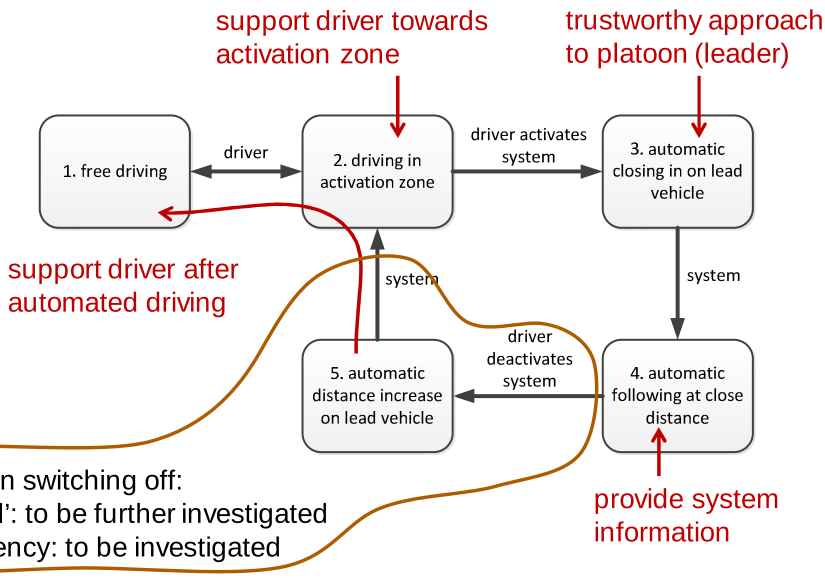


Figure 1.2 Schematic overview of the different transitions of control of the VTB initiated by the driver.

First the driver enters the road/road section where VTB system activation is allowed. Then the driver must manoeuvre the truck such that it is in a suitable position and has a suitable speed for the VTB system to take over. This way the VTB system has small control errors when it is initiated and can smoothly take over control from the driver. Once control has been taken over, the VTB system will decrease the gap between the trucks to the fuel efficient gap.

This gap is typically smaller than the gap allowed when driving manually.
After gaining the required small time gap the system will be ‘on under normal conditions’: the second truck follows the first truck at a small gap providing automated lateral and longitudinal control. The driver is not in the control loop anymore. At a specific moment in time, for example when reaching the end of the section where VTB is allowed or when reaching the destination exit, the system will increase the following gap to a normal gap size for manual driving and will hand back the control of the vehicle to the driver.

In current experiment, we choose to concentrate on switching off the VTB by the driver on request of the system in a non-emergency situation. For this use case, one of the main questions that needs to be answered is how fast the driver takes back control and whether the driver is capable of driving after a period of automated driving. Even though there are numerous studies that deal with this time to take back control (e.g. Merat et al, 2014; Tofetti et al, 2009; Willemsen, Stuiver en Hogema, 2014; Willemsen, Stuiver & Hogema, 2015), no prior studies have been done in trucks with professional truck drivers.

The final goal of the project is to develop a quantitative model that is able to estimate how long it will take for a driver to respond and how capable a driver is to drive again after having been ‘out of the loop’.

Ideally, A-VTB in comparison to a normal VTB (not being adaptive), anticipates how quickly and how well a driver can take back control, being able to adjust the settings and warnings to the specific driver, the circumstances and his current state, involving notifications that the driver soon has to regain control and support the driver in regaining situational awareness and if necessary providing stronger or less support in the driving task after regaining control by the driver.

2 Method

In order to generate data to develop a (data driven) model to estimate driver readiness to take back control, a truck driving simulator experiment was conducted.

2.1 Participants

22 participants took part in the experiment. They all held their truck driver's license for at least 8 years and drove at least 10.000 km per year (Table 2.1). On average participants were 47 years old (range 27-64), with a standard deviation of 11.5. The group consisted of 20 male and 2 female drivers. Education level was mostly MBO (13, Intermediate Vocational Education) followed by HBO (5, Higher Vocational Education), Havo (2, Senior General Secondary Education), WO (1, University Degree) and unknown (1).

Table 2.1 Driving experience and licenses.

	Car licence # years	Car mileage km/year	Truck licence # years	Truck mileage km/year	Bus license # years	Bus mileage km/year
Mean	29	18860	28	35218,7	31,1	14666,6
SD	11,5	13835,6	11,7	27508,2	12,9	13313,5
Min.	9	5000	8	10000	4	2000
Max.	46	60000	45	90000	45	40000

2.2 Truck driving simulator

The experiment was carried out in a high fidelity moving base driving simulator consisting of a DAF truck mock-up mounted on a 6DOF moving base (Van der Horst and Hogema, 2011; Figure 2.1). The road and traffic environment were projected on cylindrical screens around the vehicle. The projection system for the front view had a horizontal viewing angle of 3 x 60 = 180 degrees, realised by three projectors. The vertical viewing angle was 41 degrees (22 degrees above and 19 degrees below the neutral viewing direction). The driver could use the DAF truck's external rear view mirrors to look at two screens placed behind the vehicle displaying the environment behind. The internal rear view mirror could be used to look at a 32 inch LCD screen placed in the back of the car. Feedback of steering forces was given to the driver by means of a high-fidelity electrical torque engine. The display giving information about the automated driving system was displayed in the dashboard underneath the speedometer.

Figure 2.1 Truck simulator with moving base and cylindrical projection screen.

Automated driving system
An automated system was used that allows a truck to follow a lead truck at a relatively short following distance (up till 0.3 seconds), controlling both the longitudinal and lateral motion. The system is designed to operate on public motorways (i.e. without using dedicated lanes), initially limited to platoons of two trucks. The first truck is intended to be driven by a human operator (but is controlled by the simulator at the moment) and (once engaged) the second truck is controlled by the automated system. The participants in the driving simulator were the drivers of the second truck in the platoon. The automated system was modelled as a combination of a Cooperative Adaptive Cruise Control (CACC) controller (Ploeg et al., 2014) and a Lane Keep Assist (LKA) system. The driver could push a button normally used for cruise control on the right side of the steering wheel to switch the automated system on/off. To be able to switch the system on the driver had to drive in an 'activation zone' behind the lead truck (Figure 2.2). After activating the system by pushing the 'on/off' button the system would take over both longitudinal and lateral control. To deactivate the automated system, the driver had to push the 'on/off' button again. The automated system would then immediately transfer both longitudinal and lateral control back to the driver.

At the end of the automated driving period, the system would indicate that the driver had to take over control by displaying a large orange background text message over the display and playing an alert sound (in Dutch: "Neem de controle over"). The length of automated driving depended on the condition they drove. In the last run, which was a failing truck platoon situation, a warning sound was played and the text to take over control also displayed that the link between the trucks was no longer present. The results of this last run are presented in a separate report (Wilschut, Dufils & Willemsen, 2015).

Figure 2.2 Screen shot of the interface showing the lead truck (left) and following truck (right) withthe activation zone (dashed square) when the automation was switched on the colour changed from white to blue and the linking symbol was displayed between the two trucks.

2.3 Description of the scenarios

Participants drove on the right-hand lane (the slower lane) of a two-lane motorway behind a lead truck that was driving with an average speed of 80 km/h.
The participants were instructed to follow this lead truck and not to change lanes. There were no entries or exits on the route the participants drove. Slight curves and surrounding traffic made the experience more realistic.

For the truck simulator scenarios, several choices needed to be made. Since truck platooning is not yet available on public roads and the development is still ongoing, we decided to include scenarios that link to some of the main research questions. The main research question is about what a driver can do while the truck is in platooning mode, and whether what the driver is doing has an effect on how soon a driver can take back control. Also, since we are interested in the quality of the control, we decided to include some braking scenarios. Additionally, conditions are included with a specific transition phase, in which a driver drives closer to the lead truck during platooning (0.3 s), but with the automation increasing this headway to 0.8 s after telling the driver to take back control. In that scenario, the drivers could indicate to be ready before the actual 0.8 had been reached. The response times of these conditions and the headways that were present at the moment the driver took back control are reported. However, the driving behaviour after taking back control in the transition conditions has not been analysed due to the fact that by mistake, half of the participants received a braking action and half did not.

Each participant drove multiple scenarios in which the driver readiness was manipulated during the automated driving segment. The drivers were either instructed to pay attention and monitor the surroundings (we will call this the Ready condition), to distract themselves with an iPad (we will call this the Not Ready condition) or to close their eyes (we will call this the Eyes Closed condition).
For all conditions, the headway to the lead truck was 0.8, except for the Transition condition, where it was 0.3 and only increased to 0.8 after a driver received a warning to take back control.

In the Ready and the Not Ready condition, drivers also got a braking lead vehicle about 3 seconds after they took back control. This was to test whether they had a proper response to a more critical scenario.

Furthermore, a failing truck-platoon scenario was added, funded by Rijkswaterstaat, to investigate what kind of behaviour truck drivers tend to show when they suddenly have to take over manual control of the truck due to a system error in a very critical situation. As said, these results are described in a separate report for Rijkswaterstaat.

The drivers performed 9 different runs, where the runs differed in settings for following parameters/conditions as displayed in the figure below (Figure 2.3).
The eyes closed condition was always in the 6^{th} run. The RWS scenario was always the last run.

In all drives, participants would initially control the truck themselves and switch the automated (VTB) system on by driving in the correct position behind the lead truck and pressing the button. After engaging the system they would either be instructed to stay alert, be distracted or close their eyes. When the system indicated they had to take back control, they were asked to press the button to actually get back control when they thought they were ready to take back control. If necessary, depending on the condition, they would first have to put away the tablet or open their eyes, it was also left to the driver on how he or she wanted to do this.

The actual duration of the automated driving differed a bit between conditions. The Ready condition was consciously kept somewhat shorter than the Not Ready condition and the Eyes Closed condition, to increase the possibility that drivers were still paying attention and were alert. The Not Ready and Eyes Closed conditions were a bit longer to increase the chance of the driver being out-of-the-loop.

In some events, the lead truck would brake just after the driver got back control of the truck. This was done in order to have some idea about the quality of the readiness to take back control. The brake event would always take place in the 3rd and 5th run. A brake event would take place about 3 seconds after the driver switched the system off. The lead truck would brake for 2 seconds with -5 m/s^2.

The final run was the failing truck platoon scenario. During this scenario, the participants had to be attentive to the traffic (ready) and after 6500 m an auditory warning was issued that the control would be switched back to manual control. The lead truck swerved making an emergency maneuver to the left lane or the hard shoulder. And a stationary vehicle was positioned within 200 m. The participant had to respond to this vehicle or an accident would take place.

An overview of the conditions is presented in Figure 2.3.

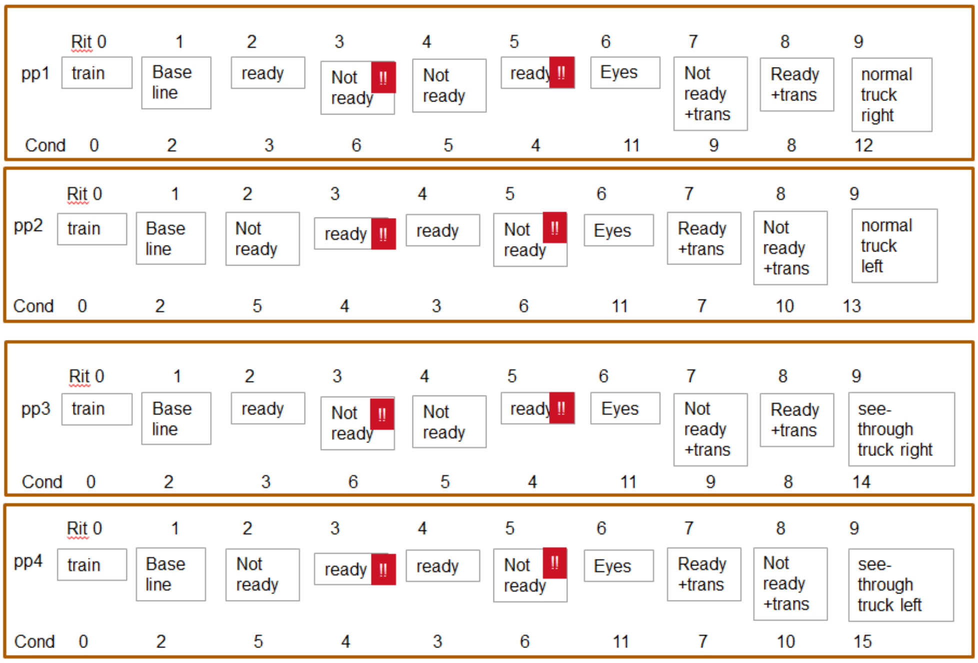


Figure 2.3 The four different orders of the scenarios and in red exclamation marks the runs in which the brake event took place. By accident, conditions 8 and 10 contained braking events as well.

2.4 Dependent measures

From the driving simulator driver behavioural data was collected e.g. acceleration, lateral position, time headway (THW) etc. Furthermore, the state of the automation, the timing of HMI messages, button presses and brake response times were recorded. The interval from when the braking light of the preceding truck switched on till the driver engaging the brake was taken as the driver's brake response time.

Heart rate (bpm) and Inter Beat Intervals (IBIs) were derived from the Mio wristband and the Microsoft wristband. The Microsoft wrist band also measured acceleration in three directions and rotational speeds in three directions.

Hand positions on the steering wheel were recorded with four sensors that were mounted on the steering wheel.

A pressure mat was used on the seat of the driver. This was used to measure differences in position while being out of the loop or just before taking back control again. These data will be used for feeding into the driver readiness model, but will not be reported in the current report.

A Smart Eye tracker with four cameras recorded the eye movements during the experiment. Regions of Interest (ROIs) were defined, for instance, mirrors, dashboard, windscreen etc. and used for the analysis. However, the eye movement data needed additional manual corrections since when drivers looked at the i-Pad, no eye movements could be recorded, and with very short glances to the road the system was not sensitive enough. Due to the manual corrections, a second independent observer needed to perform the same analysis and an interrater agreement was needed to be calculated with a second observer's data.

Since this took more time, these data will be reported separately and will not be included in this report.

Camera images of the hands, feet and body posture of the driver were recorded. As well as a recording of a camera positioned in the cabin to record the virtual presentation of the outside world and traffic. Since very diverse behaviour of hand, feet and body postures during take over were captured, no statistical analyses could be done and the data will not be reported in this document. However, the data are extremely valuable for our driver readiness estimation model which is our ultimate goal of this project.

The acceptance scale (van der Laan, 1997) was administered before and after the experiment. The acceptance scale consisted of nine questions with items scored -2 to +2 on a 5-point Likert scale. Scores where combined to derive the scales on two dimensions: Usefulness and Satisfaction.

The rating scale of mental effort (RSME; in Dutch: Beoordelingsschaal mentale inspanning (BSMI); Zijlstra, 1993) was used which is a one-dimensional scale where ratings of invested effort are indicated by a cross on a continuous line. The range of the scale is 0 “absolutely no effort” to 150 “extreme effort”.

The scale is scored by the measurement of the distance from the origin of the scale to the mark in mm. The RSME is capable of self-reported measurement of workload and has shown to be more sensitive to workload changes than the NASA-TLX (Veltman & Gaillard, 1998). After every run the participants filled in this scale for the period of automatic driving and manual driving i.e. after they pressed the button.

Trust: Two additional questions were asked before the experiment started, and just before the failing truck platoon scenario. The questions were about trust in automated driving on the road and in the simulator. Trust in automated driving was rated on a visual analogue scale from 0-100%.

Situational Awareness: In all runs there was one unique vehicle placed standing still on the hard shoulder during the automated driving segment to assess situational awareness. The hypothesis was that participants would spot the vehicles during the Ready conditions, but not during the Not ready or Eyes Closed conditions. We refer to this dependent measure as Situation Awareness. Situational Awareness was assessed by showing participants screenshots of the vehicle placed on the hard shoulder during the automated driving segment in each run of the experiment (Figure 2.4). These vehicles were all unique and four control pictures were added to the questionnaires that were never shown during the experiment. In total participants had to choose from 10 pictures which vehicle had been present. For each picture the participant had to indicate whether or not they had seen the vehicle during the experiment and with which certainty (0-100% certainty).

Figure 2.4 Examples of image shown to assess Situational awareness.

Experimental procedure
Prior to driving, the participants filled in a questionnaire about experience, acceptance and trust in the system. Eye tracker calibrations were done and the participant put on a Mio and a Microsoft wristband to measure heart rate. In the driving simulator, all participants started with a training session to get familiar with the driving simulator and the automated driving system. During training they were asked to perform the hooking on and hooking off procedure multiple times (min. 3) until they felt comfortable with it. After training, all participants started with a baseline run, i.e. without the automated system, hence normal manual truck driving. This was a normal drive on the same road as they would drive on in the conditions with the system. There was a lead truck in front of them which they were not allowed to overtake. This ensured that all participants were more or less driving at similar speeds. The manual drive also had a braking event (in order to compare the response during manual driving with driver response after take-over). After the baseline condition, they would either get the Ready or the Not ready condition. The brake event would always take place in the 3rd and 5th run (note that in the Ready and the Not Ready condition, all participants drove with and without a brake event). The Eyes closed condition was always the 6th run.
Then the following 2 runs were the Transition conditions with the short THW (0.3 s) and longer transition period. Participants always drove a Ready condition with Transition and a Not ready condition with Transition (accidentally one of these conditions would have a brake event, making the Ready Transition condition incomparable to the Not ready Transition Condition in terms of driving behaviour after the take-over). As mentioned before, the last run was the RWS run with the very critical event which will not be reported here.

After each run the rating scale of mental effort (RSME) was filled in while the truck drivers were sitting in the simulator. After completing all regular runs (1-8), participants filled in the acceptance questionnaire and trust scales for a second time, to see if any changes in opinion about the system had taken place. They also filled in the situational awareness questions. After this they drove the final failing truck platoon scenario and were asked again if they trusted the system and were debriefed and the experiment was completed for them.

Statistical analyses
Using Statistica 12.7 version, all measures were analysed using General Linear Model Repeated Measurement analysis of variance, reporting significance levels at $p<.05$. Post hoc analysis (pairwise comparisons) was performed using Bonferroni comparisons. In order to provide a coherent overview, main effects of condition were always used for the combinations: Baseline (braking), Ready (braking) and Not ready (braking) and for the combination Ready (no brake), Not ready (no brake) and Eyes closed (no brake).

Also the conditions in which a transition was provided before the control was given back to the driver will be discussed separately, but only for the effect on driver response time and the headway at which drivers took back control.

3 Results

This chapter presents the statistical analysis of the simulator experiment for relevant driving indicators. It should be noted that the manual (also called baseline) condition was driven once by each driver and always contained the braking vehicle in front. Also the eyes closed conditions was driven once, without a braking preceding vehicle.

3.1 Driver response time for readiness to take back control

After receiving a tone and visual warning to take back control, drivers pressed a button to indicate when they thought they were ready to take back control and would immediately get back control. Response times were measured as the time between the first activation of the warning until the driver's button press.

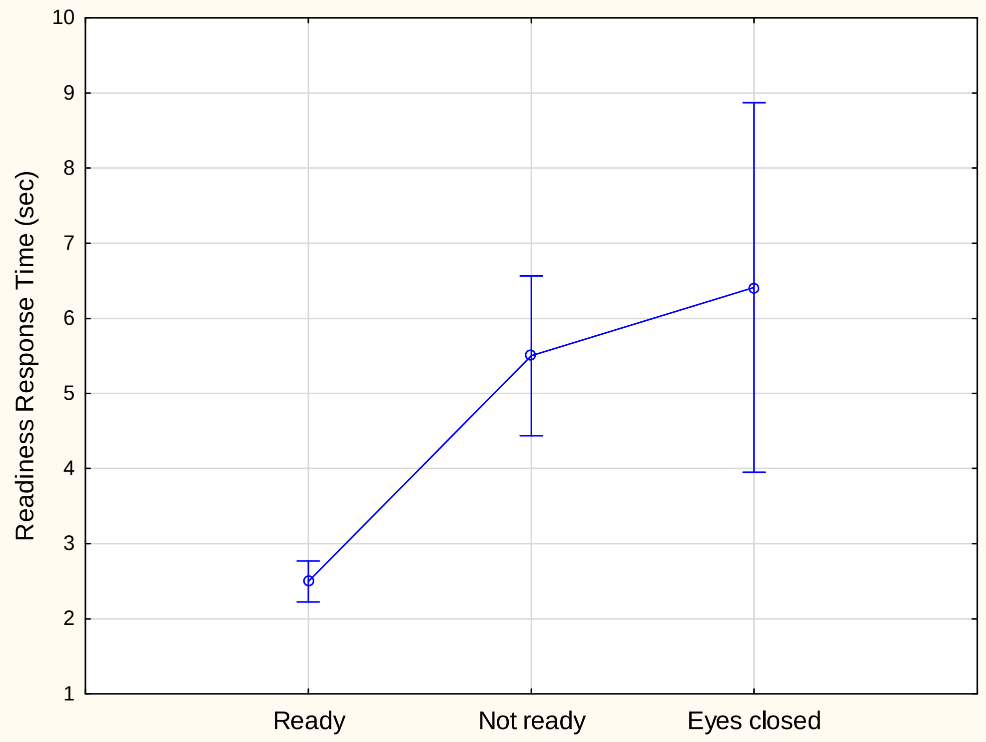


Figure 3.1 Response times of drivers after the request to take back control. Vertical bars denote 0.95 confidence intervals.

Repeated measures ANOVA showed a main effect of Condition [$F(2,24) = 8.68, p < .001$]. Pairwise comparisons show that there were significant differences in Response time between 'Ready' (Driver monitoring the surroundings), 'Not ready' (i-Pad) and 'Eyes closed'. In the Ready Condition, button response times were significantly faster than in the Not Ready ($p<0.02$) and the Eyes Closed condition ($p<0.002$). Also, the variance differed a lot between conditions. The minimum and the maximum response time for the different conditions was 1.75 – 3.8 seconds for the Ready condition, 3.07 – 8.54 seconds for the Not Ready condition and 2.33 -16.79 seconds for the Eyes Closed condition.

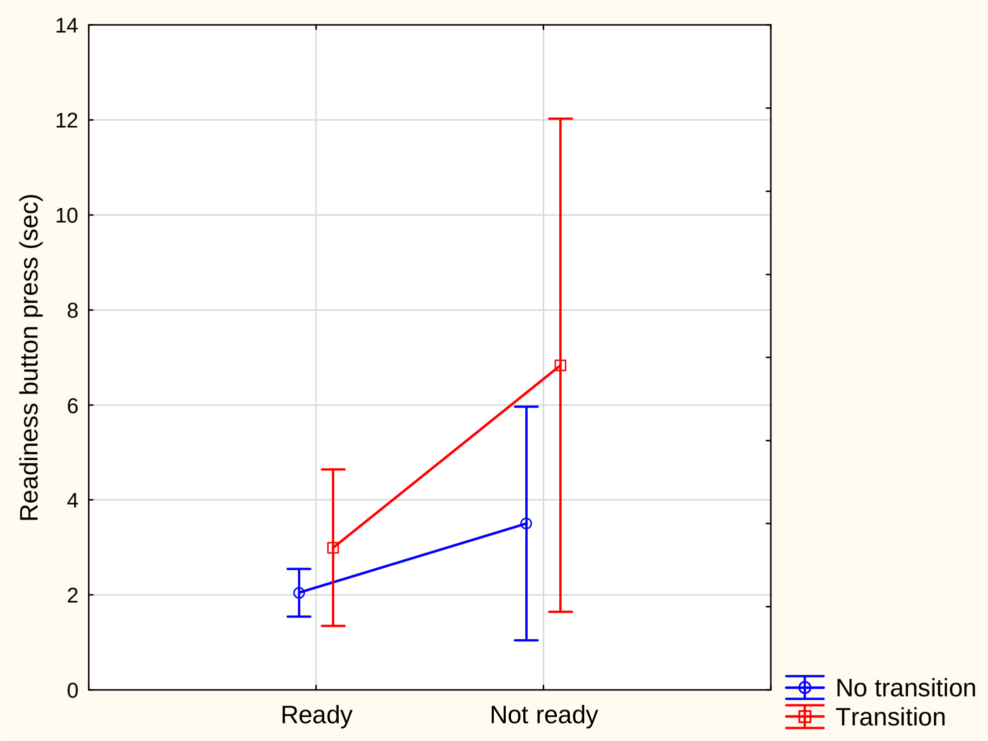


Figure 3.2 Response times of drivers after the request to take back control in the braking and transition conditions. Vertical bars denote 0.95 confidence intervals.

In the conditions in which the lead vehicle would brake just after take-over (when drivers responded they would not have any indication that the vehicle would brake, so for drivers the brake conditions were similar to the non-brake conditions when indicating to be ready), or the conditions in which the system would automatically increase the THW from 0.3 to 0.8 after the warning to take back control, there was also a significant difference in response times between the ‘Ready’ and the ‘Not ready’ conditions ($p < 0.05$), again with the Ready condition having faster button response times and less variance.

3.2 Longitudinal control

3.2.1 Mean speed after button press

After truck drivers pressed the button to regain control of the vehicle, the speed was analysed for 45 seconds.

For the braking conditions, there was a main effect of Condition on mean speed during 45 seconds after the button press [$F(2,34) = 26.16$; $p < 0.0001$]. Pairwise comparisons show that mean speeds for the Ready and the Not Ready condition are significantly lower than for the manual driving (baseline) condition (both $p<0.00001$). For manual driving, the behaviour was analysed according to the platooning braking events, linking the braking events in time, assuming that 3 seconds before the braking events, participants ‘would have gotten back control’ in the reference condition. This effect is shown in Figure 3.3.

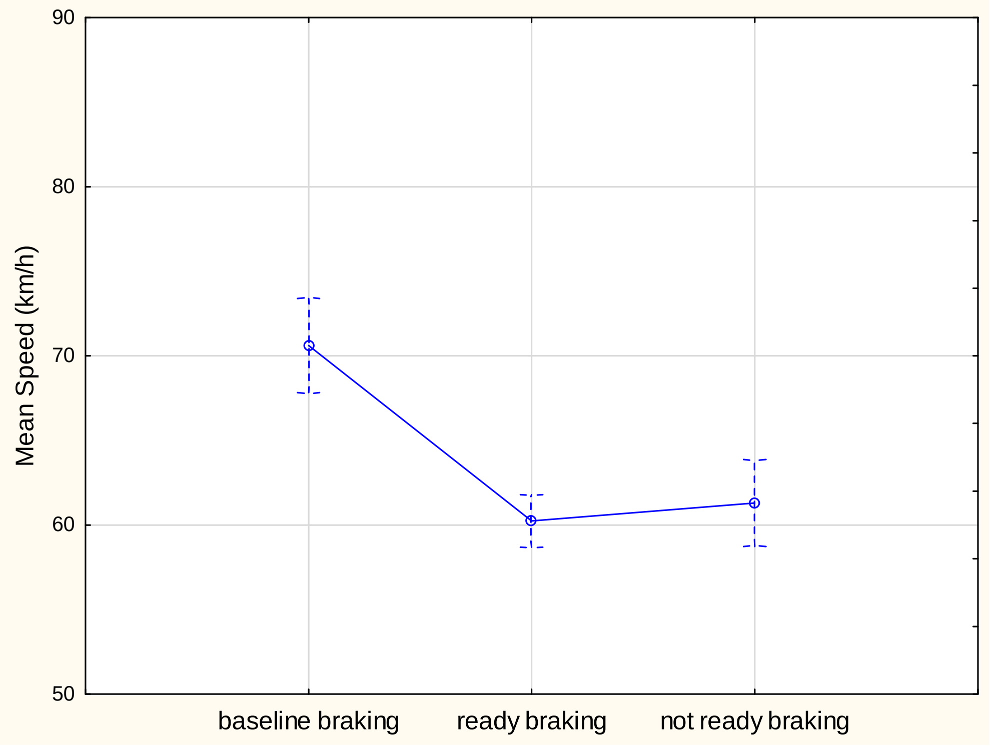


Figure 3.3 The mean speed for the 45 seconds after the take-over from the driver for the braking events. Vertical bars denote 0.95 confidence intervals.

For the situations without a braking event (Ready, Not ready and Eyes closed), there was no main effect of condition in speed after the control was handed back to the driver.

If we specifically analyse the speed in the 10 seconds after the transition in the brake events, this effect is also present [$F(2,36) = 32.31$, $p<.000001$], with even lower speeds since the braking event had a stronger effect on mean speed in this shorter period of time.

3.2.2 *Standard deviation speed after driver taking back control*

The standard deviation of the mean speed in the 45 seconds after the control was taken back by the driver was analysed.

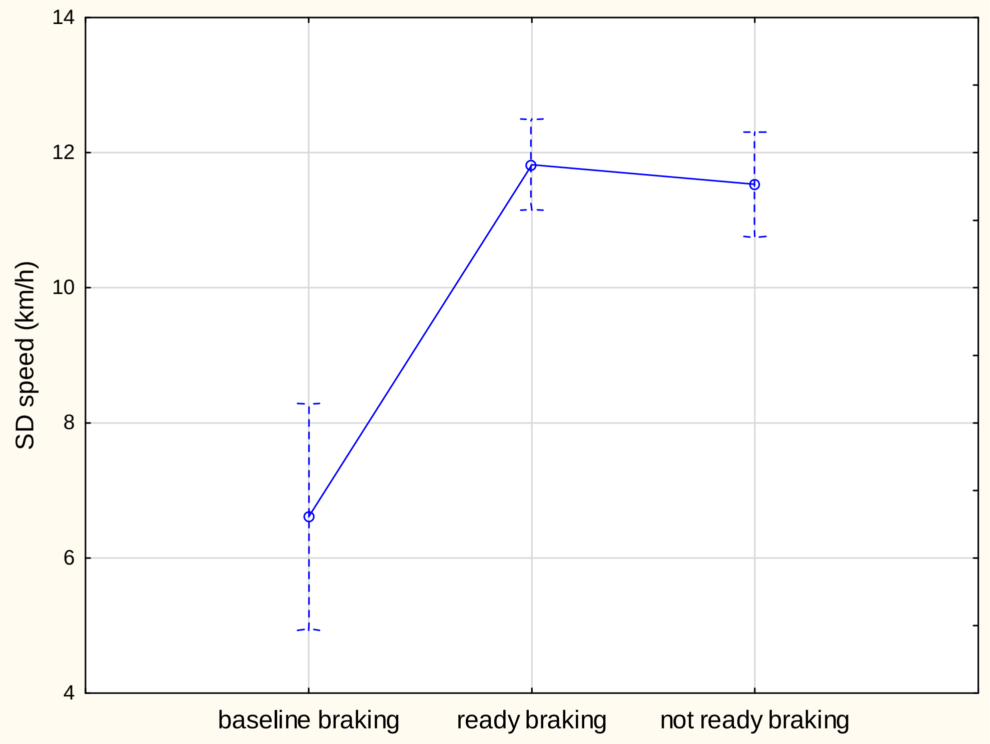


Figure 3.4 Standard deviation of speed for the 45 seconds after getting back control (and with braking event). Vertical bars denote 0.95 confidence intervals.

There was a main effect of condition [F(2,34) = 37.49, p < 0.00016] with the braking events, with a significantly higher standard deviation for the Ready and the Not Ready condition (both p<0.00001, shown in Figure 3.4).
For the conditions without braking events, there was also a main effect of Condition [F(2,40) = 5.51, p<0.006]. This effect is shown in Figure 3.5. Pairwise comparisons showed that the Not Ready condition has a higher SD speed than the Ready condition (p < 0.006).

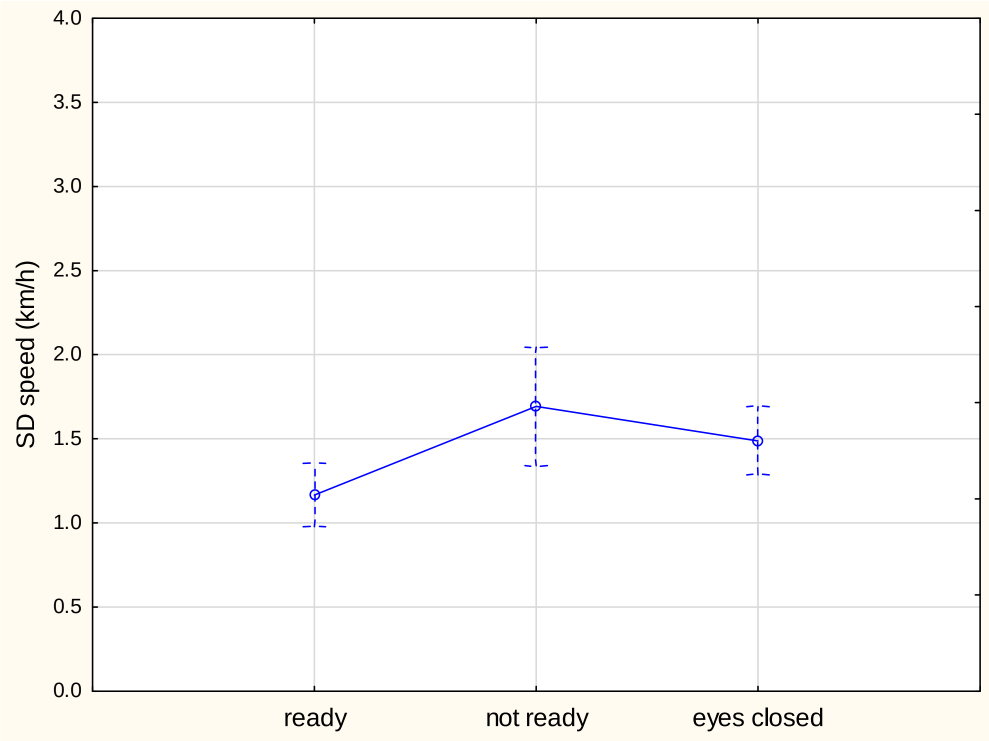


Figure 3.5 Standard deviation of speed 45 seconds after taking back control (no braking event). Vertical bars denote 0.95 confidence intervals.

When we analyse the same data for 10 seconds after the transition in the braking conditions, we again find a main effect of Condition [F(2,34)=37.46, p<0.00001], but this time only a significant difference between Baseline driving (manual driving) and the Ready and the Not Ready condition (p<0.03). This effect is shown in Figure 3.6. There was no significant difference between the Ready and Not Ready condition.

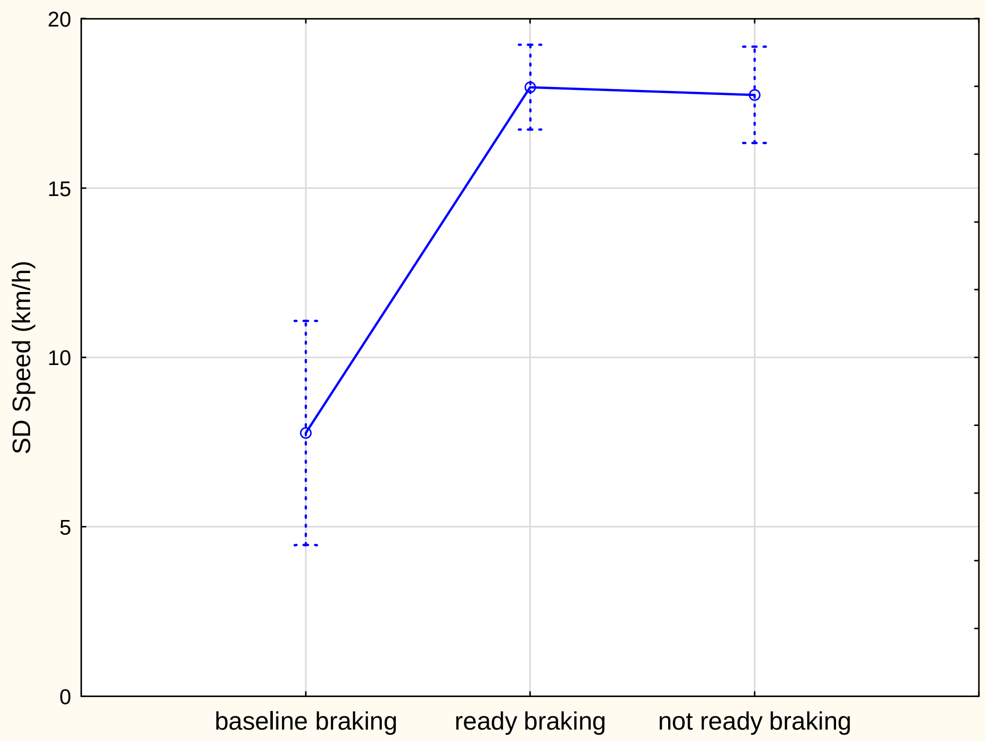


Figure 3.6 Standard deviation of speed for the 10 seconds after taking back control (braking events). Vertical bars denote 0.95 confidence intervals.

In the conditions without braking, for the 10 seconds after the transition, we again find a main effect of Condition [F(2,40) = 4.25, p<0.002], with the Not Ready and the Eyes Closed condition having significantly higher SD speed than the Ready condition (both 0<0.00001).

3.2.3 *Brake response time*

For the conditions in which the lead truck braked as soon as the control was handed back to the driver, brake response times were calculated. The lead truck would brake about 3 seconds after the driver took back manual control. The interval from when the braking lights of the preceding truck switched on to the driver engaging the brake was taken as the driver's brake response time. Also for the manual/baseline conditions the brake response times to a braking lead truck were calculated. There is a main effect of Condition [F(2,32)=21.66, p<0.00001], with the Ready and the Not Ready condition having significantly shorter response times than in the manual condition (p<0.00001).The results are shown in Figure 3.7.

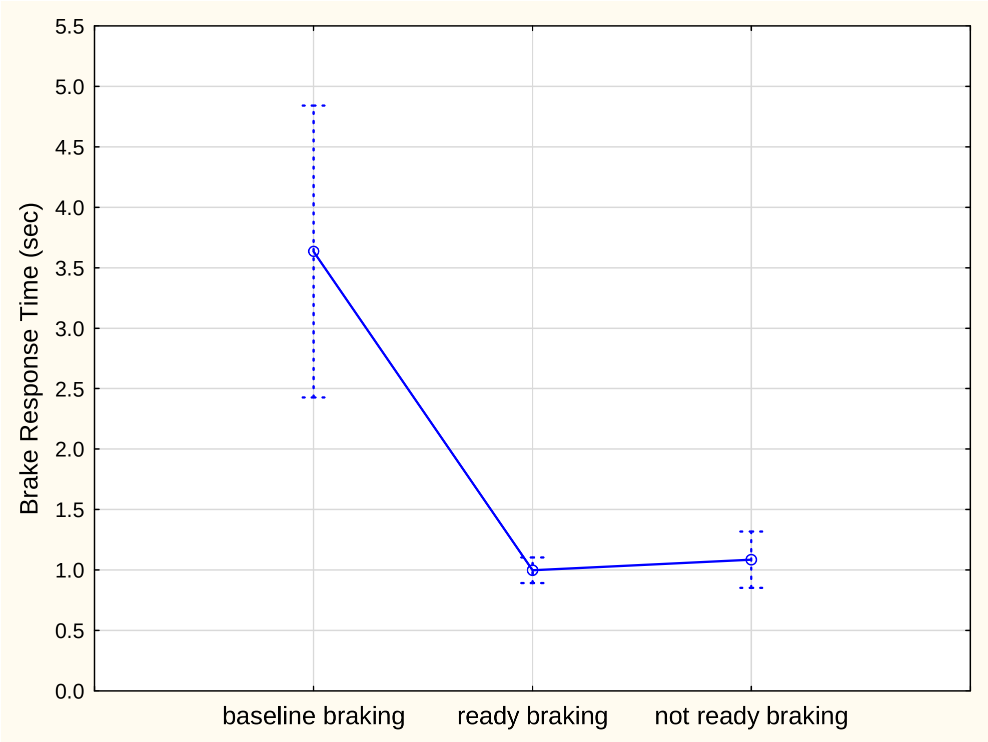


Figure 3.7 Brake response times for the different conditions with a braking event. Vertical bars denote 0.95 confidence intervals.

The main effect of Condition can also be the result of the manual condition having a longer mean THW than the automated conditions when the braking event started. When the data from 10 seconds before the braking event is analysed, we indeed see that there is a main effect of condition here as well, with the baseline condition having longer mean THW than the other two conditions [$F(2,36)=48.64$, $p<0.0001$]. This also means that there was less need for an urgent brake response in the baseline conditions. These results are presented in Figure 3.8.

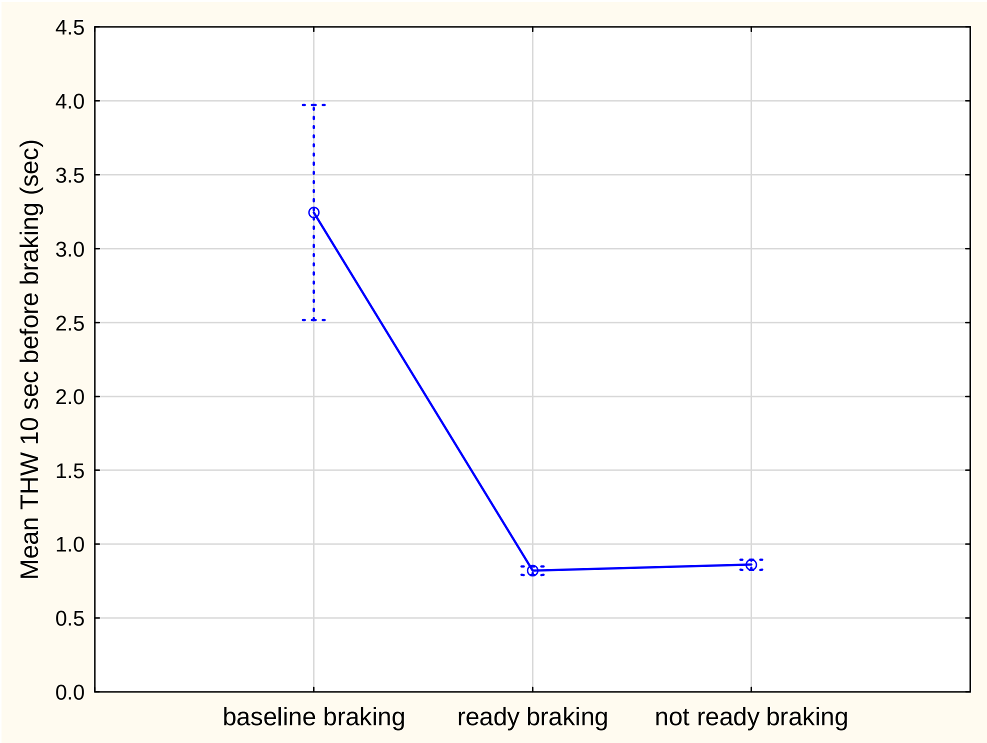


Figure 3.8 The mean time headway for the different conditions before the take over from the driver. Vertical bars denote 0.95 confidence intervals.

3.2.4 *Minimum THW*

When we look into the minimum time headway in the 45 seconds after take over, there was no main effect, neither for the braking, nor for the non-braking events. When we limit the analysed time period to 10 seconds after taking over control, we do see an effect of Condition for the braking conditions [$F(2,34)=37.13$, $p<0.0001$]. The baseline condition shows longer mean THW than the other two conditions condition ($p<0.0001$). This is as said also related to the higher THW before the braking event, as is shown in Figure 3.9.

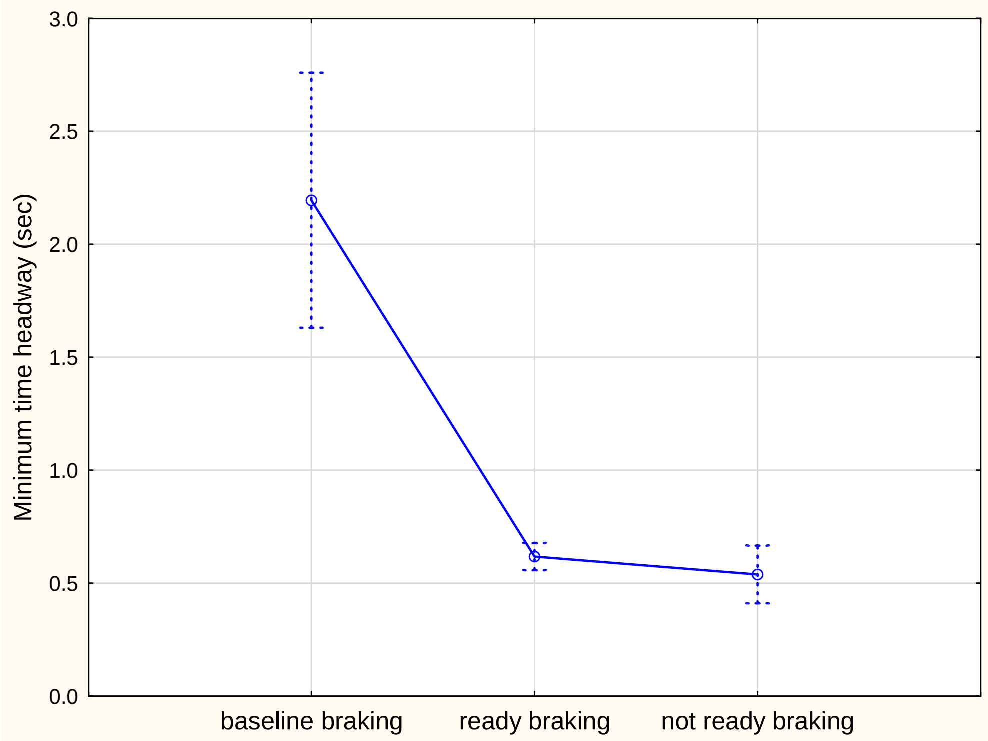


Figure 3.9 The minimum time headways for the 10 seconds after take-over for the braking conditions. Vertical bars denote 0.95 confidence intervals.

This means that despite the lower response times, the urgency of the braking situation was less for the manual driving condition compared to the Ready and the Not Ready condition.

In the non braking events, we also see a main effect for Condition [$F(2,40)=5.35$, $p<0.009$], with the Ready condition having a very small but significantly lower minimum THW than in the Eyes Closed condition ($p<0.009$, as shown in Figure 3.10).

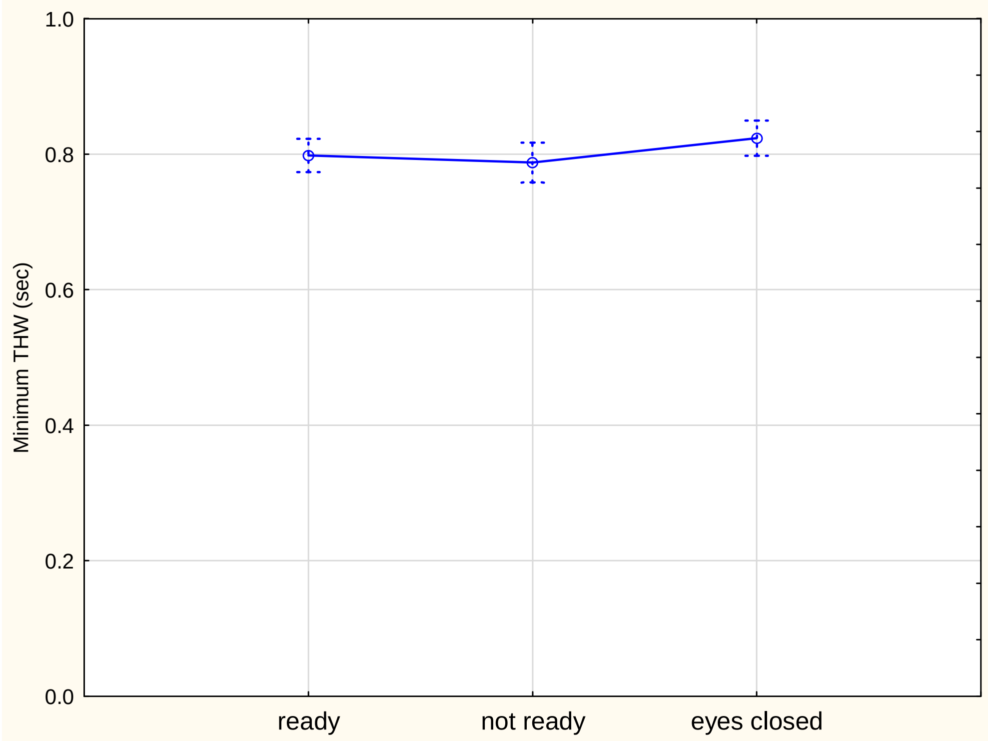


Figure 3.10 The minimum time headways for the 10 seconds after take-over for the non-braking conditions. Vertical bars denote 0.95 confidence intervals.

3.2.5 Minimum Time To Collision (TTCmin)

For the conditions in which there was a brake event, the minimum time to collision was calculated. There was a main effect of Condition [$F(2,32)=22.41$, $p<0.0001$] with both the Ready and the Not Ready condition having a significantly lower minimum TTC than the baseline condition ($p<0.0001$).

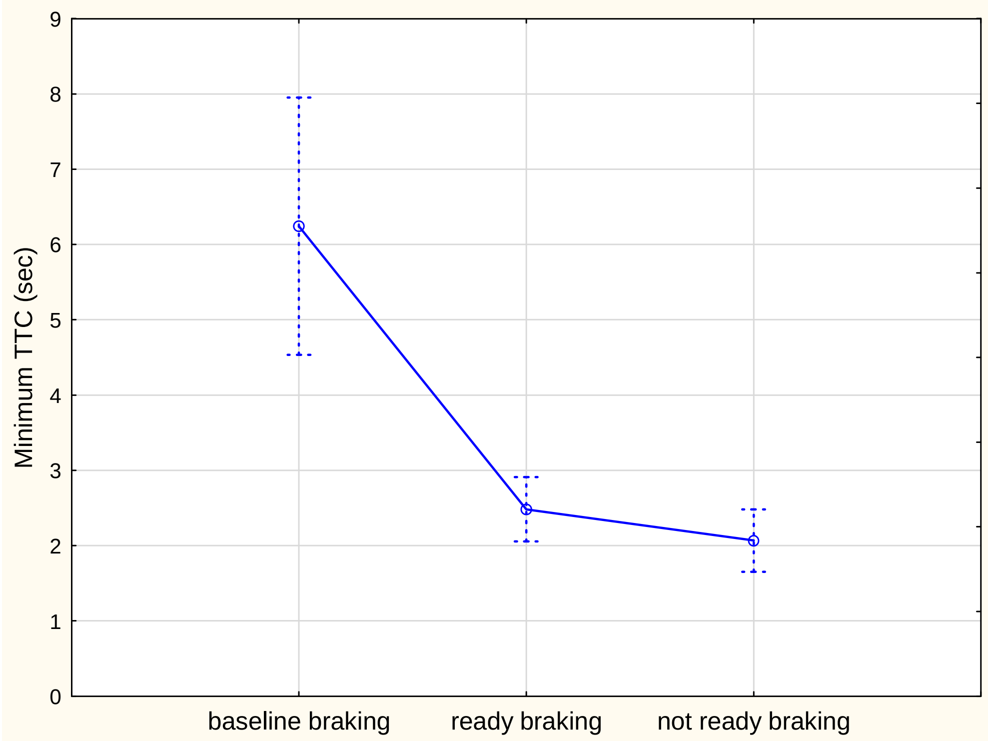


Figure 3.11 The minimum Time to Collision (TTC) for the baseline, the Ready and the Not ready condition for 10 seconds after the transition

When analysing the data for only 10 seconds after the take-over, the results are the same. This is due to the fact that the lowest TTCs were always present in the 10 seconds after the take-over. This is shown in Figure 3.11. Vertical bars denote 0.95 confidence intervals.

3.3 Lateral control

Besides analysing longitudinal results, we also analysed lateral behaviour after the transition of control back to manual driving.

3.3.1 Standard deviation lateral position (SDLP)

For the braking events, there was no effect of Condition in the 45 seconds after the transition of control for the braking events. However for the non-braking events, there was a main effect of condition [$F(2,40)=4.32$, $p<0.02$], with a significantly higher SDLP for the Not Ready condition compared to the Ready condition ($p<0.02$), as shown in Figure 3.12.

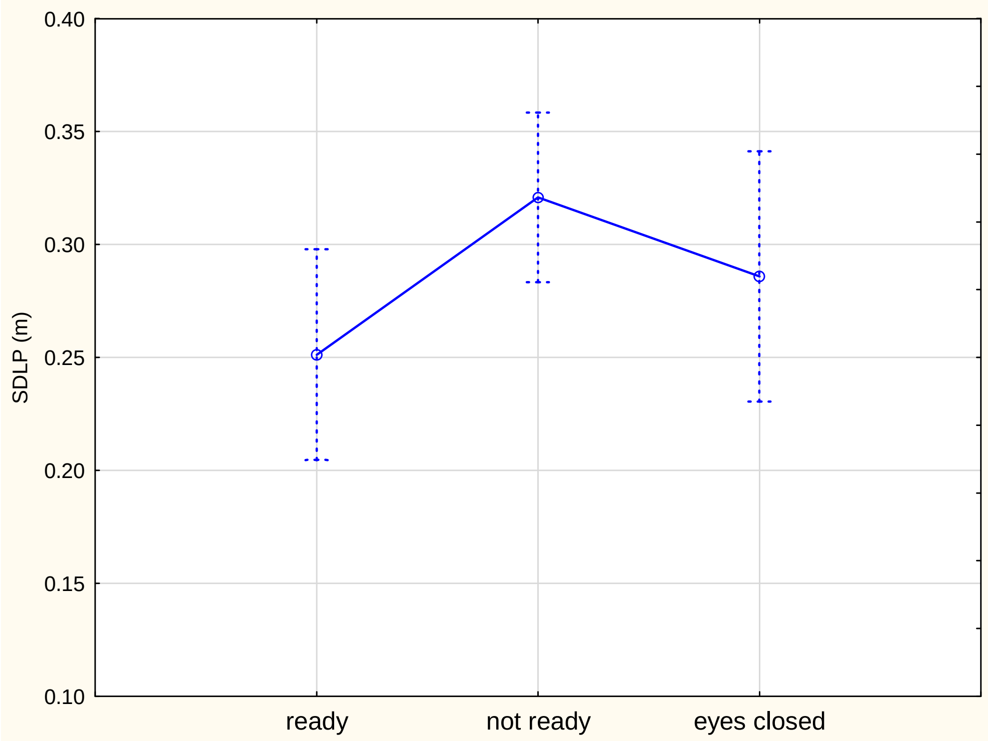


Figure 3.12 The standard deviation of the lateral position for the three non-braking situations 45 seconds after taking back control. Vertical bars denote 0.95 confidence intervals.

When analyzing the results for the 10 seconds after the transition, there is no main effect of condition in either the braking or the non-braking events.

3.3.2 *Steering Reversal Rate (SRR)*

The steering reversal rate is the proportion of absolute number of counted steering reversals per time unit (this case per second). It is one of the indications for strenuous steering behaviour. The SRR is calculated here as mean value per second. Often in literature this is used as mean value per minute, but since we also wanted to analyse the data in more detail in time intervals shorter or longer than a minute, the value per second seemed more suitable in this case. This was done by dividing the reversals (with a gap of 1 degree) by number of seconds.

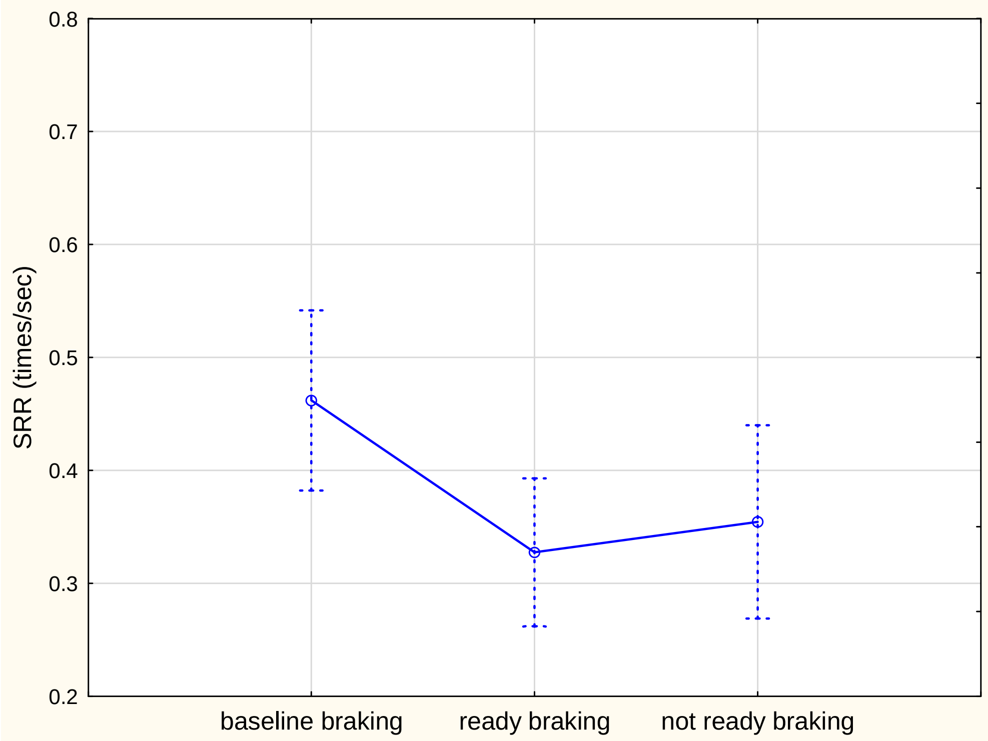


Figure 3.13 Steering reversal rate for the 45 seconds after take-over for the three braking conditions. Vertical bars denote 0.95 confidence intervals.

There is a significant difference of condition in the braking events on SRR [$F(2,36) = 10.03$, $p<0.003$], with pairwise comparisons showing the highest SRR for manual driving compared to the Ready condition ($p < 0.0005$) and the Not ready condition (0.005), see Figure 3.13. There was no difference between Ready or Not ready.

When we look at the non-braking events, we also find a main effect of Condition [$F(2,40) = 3.70$, $p<0.03$], with significantly higher SRR for the Not Ready condition compared to the Eyes Closed condition ($p<0.04$), see Figure 3.14. However this effect disappears when we only analyse 10 seconds after the take-over.

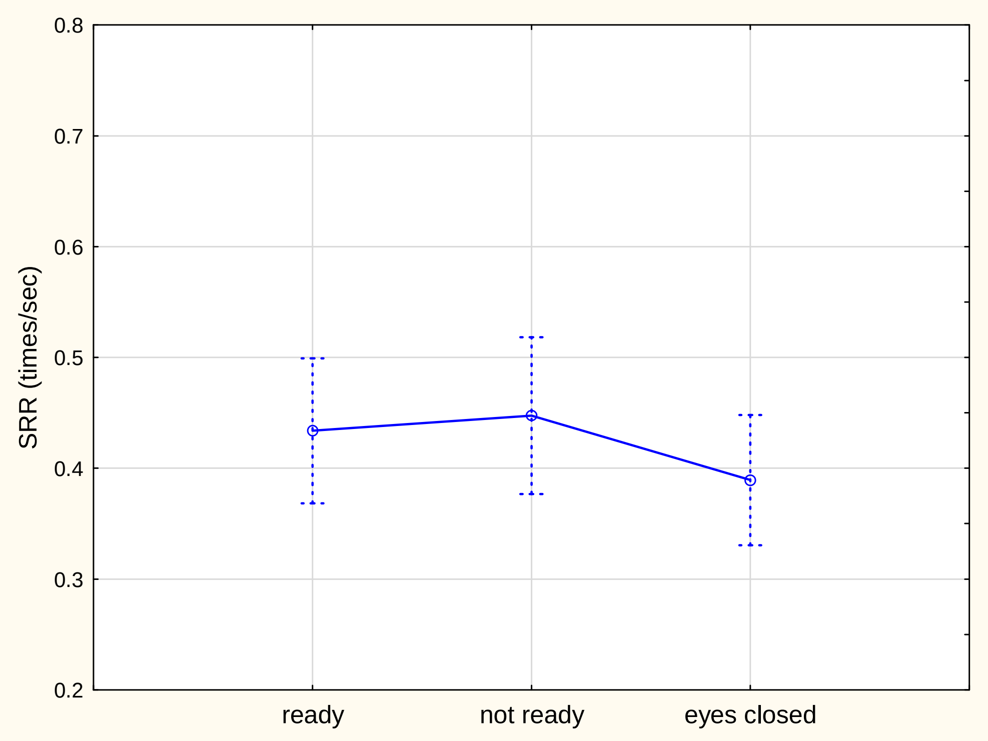


Figure 3.14 Steering reversal rate for the 45 seconds after take-over for the non-braking conditions. Vertical bars denote 0.95 confidence intervals.

When we analyse the data for the 10 seconds directly after the TOC request, there is also a main effect of Condition [$F(2,36)=4.10$, $p<0.02$] in the braking events, with the Baseline condition having higher SRR values than the Not Ready condition ($p<0.02$), see Figure 3.15.

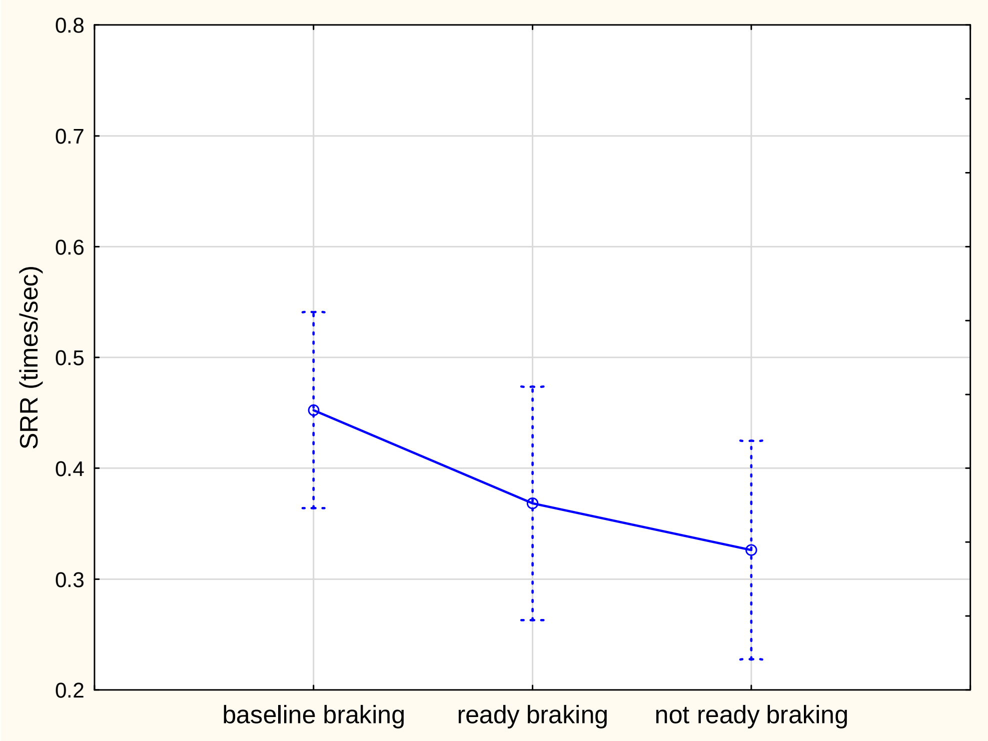


Figure 3.15 Steering reversal rate for the 10 seconds after take-over for the three braking conditions. Vertical bars denote 0.95 confidence intervals.

3.3.3 Minimum Time to line crossing (TLC).

For the minimum TLC, it was not possible to do an ANOVA since some variables did not have any variance since in various conditions the minimum TLC was 0 for all conditions in which people had exceeded the lane marking. Therefore, the data are just plotted in Figure 3.16.

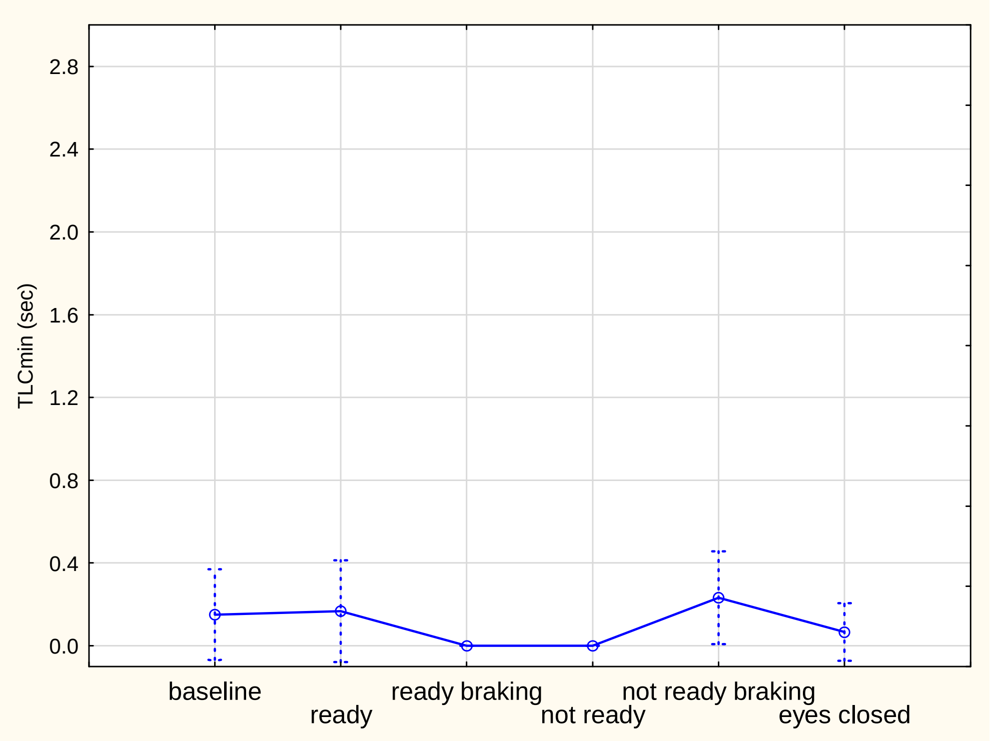


Figure 3.16 The minimum time-to-line crossing for the 45 seconds after take-over for the three braking conditions. Vertical bars denote 0.95 confidence intervals.

For the 10 seconds after take-over, there were no significant differences between conditions in the braking events, nor in the non-braking events.

3.3.4 Lane exceedance

For the different conditions, we calculated the percentage of time that a participant was driving outside of the lane. There was a main effect of condition for the braking events in the 45 seconds after take-over [$F(2, 36)=4.9636$, $p<.012$], with somewhat lower percentage of lane exceedance in the Not Ready condition compared to the Ready condition see Figure 3.17.

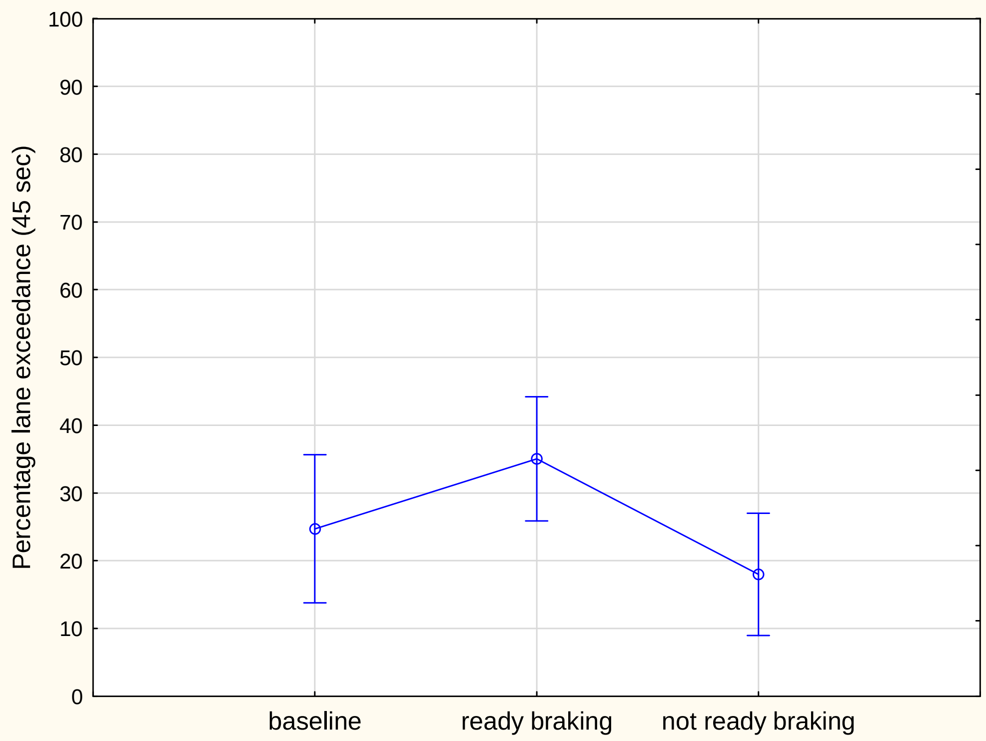


Figure 3.17 Percentage lane crossings for the different braking conditions 45 seconds after the take-over. Vertical bars denote 0.95 confidence intervals.

For the non-braking events, there were no differences found between conditions. For the 10 seconds after take over, there were no significant differences between conditions in either the braking events or the non-braking events.

3.3.5 *Hands on the steering wheel and feet at pedals*

From the experiment, it was interesting to see whether drivers would keep their hands on the steering wheel when they were in automated mode, and whether they would have both hands on the steering wheel right after they reclaimed control. Since it is very time consuming to analyse video manually, we wanted to see whether it was possible to use TNO knowledge on automated video analysis to do this based on pattern recognition.

For the different conditions, the percentage of time that during 45 seconds before take-over either the left or the right hand (independently so they could also have both hands on the wheel) was on the wheel is presented in Figure 3.19.

The figure shows that there is much random variation in the data, even for similar conditions. For example, participants could not see a difference between the brake and the non-brake events before the actual take-over. These conditions were similar. Besides that, there is much variation in similar conditions. There does not seem to be a systematic effect of Condition on hands on the wheel. Interestingly enough, not all drivers seem to have both hands on the steering wheel in the situation after they received back the control. When comparing some of the automatic video analysis data with the actual video images, it was shown that the automated video analysis was not 100% reliable.

Sometimes when drivers had the iPad close to the steering wheel, or part of their body between the camera and the steering wheel, this was scored by the software as 'hand on wheel'. In future work, the analysis of hand data and body position will also be done manually in order to improve the automated video analyses.
The results from the automated video analyses are shown in Figure 3.18.

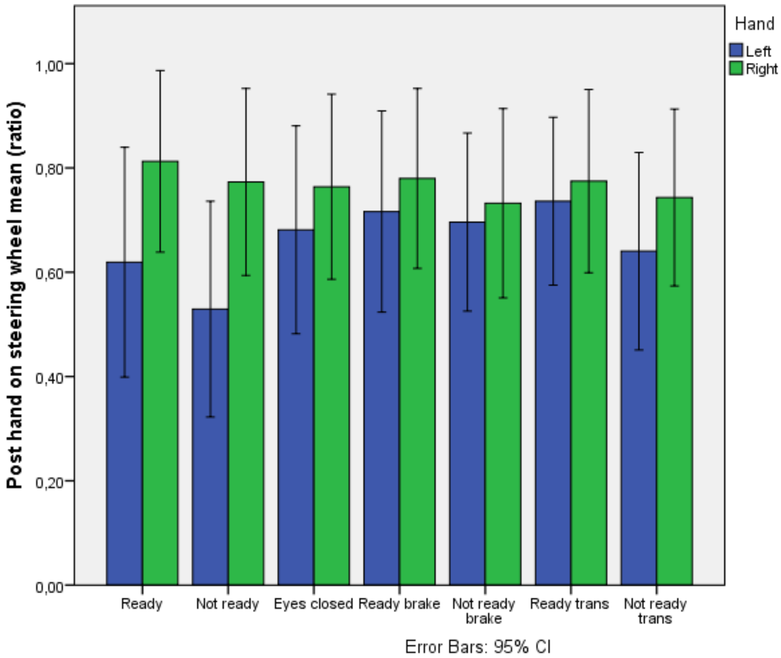


Figure 3.18 The ratio of the hands (left and/or right) on the steering wheel 45 seconds after the take-over.

Based on some of the checks we did, we decided that we needed to change the software and do more manual checks in order to make sure that the data are 100% reliable. The idea that there is potential for automatic analyses of these type of data based on video, however, was shown, although we are not there yet. The same holds for the video recordings for feet position compared to the gas and brake pedals. Therefore, it was put in the plans for 2016.

3.4 Heart rate data

Every participant wore 2 smart bands: the Mio smart band and the Microsoft band in order to be able to make a comparison between the two. The latter one also collected movement data: acceleration in three dimensions (x,y,z) and rotation speed along three perpendicular axes (yaw, pitch, roll). Participants wore the two bands at the same time, one on each wrist.

Our analysis was aimed to see whether these relatively simple and cheap devices could be used to derive information about the drivers' performance.

Part of our analysis is aimed at comparing the results of these bands. Since we did not want to use formal heart rate measurements attached close to the heart region (ECG), we cannot conclude on the precision of each individual band because of the lack of a ground truth. We found a low correlation between the measurements of the two bands, with a correlation of only 0.098.

An example of one participant
(nr 20) for one condition (6) is shown in Figure 3.19, with very large differences between the two types of bands.

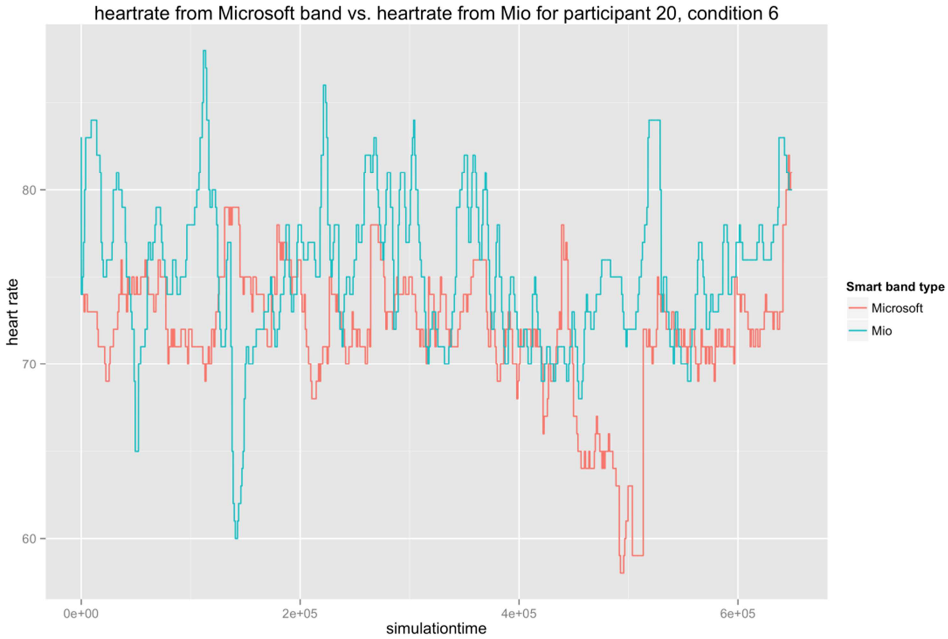


Figure 3.19 Heart rate from Microsoft compared with heart rate from Mio for participant 20 in condition 6.

To get an indication of the overall correlation between the two bands, we plotted all 2 million measurements of the two bands. Each dot in Figure 3.20 represents a moment in time at which the output of both bands has been measured.
Ideally, these dots would lie on the x=y line, indicating that they give the same measurement at the same time. Even an absolute difference would be OK, e.g. when one band structurally gives a higher measurement than the other.
The correlation over all measurements, however, is only 0.28.

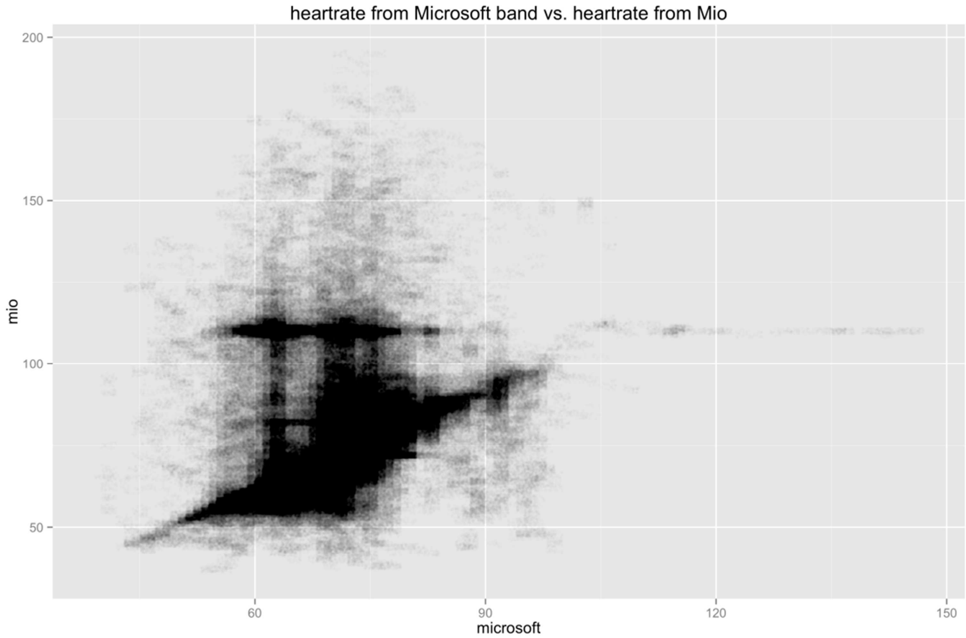


Figure 3.20 Scatterplot of all measurements of the two smart bands, for all participants and all conditions.

The horizontal and vertical bands in the figure suggest that one of the two bands may be malfunctioning in some scenarios, and give a constant value, while the other may be functioning fine. Therefore, we calculated the correlation between the two bands for each participant and each condition separately. Figure 3.21 shows that there are significant differences between the various participants and conditions: in some conditions the smart bands correlate, in others they don't, and in some the correlation is negative: if one band measures a high value, the other measures a low value and the other way around. Apart from participant 25 where the correlation is positive in almost all conditions, there are no other participants that have a high overall score. So the performance of the smart bands is not person dependent, nor condition dependent.

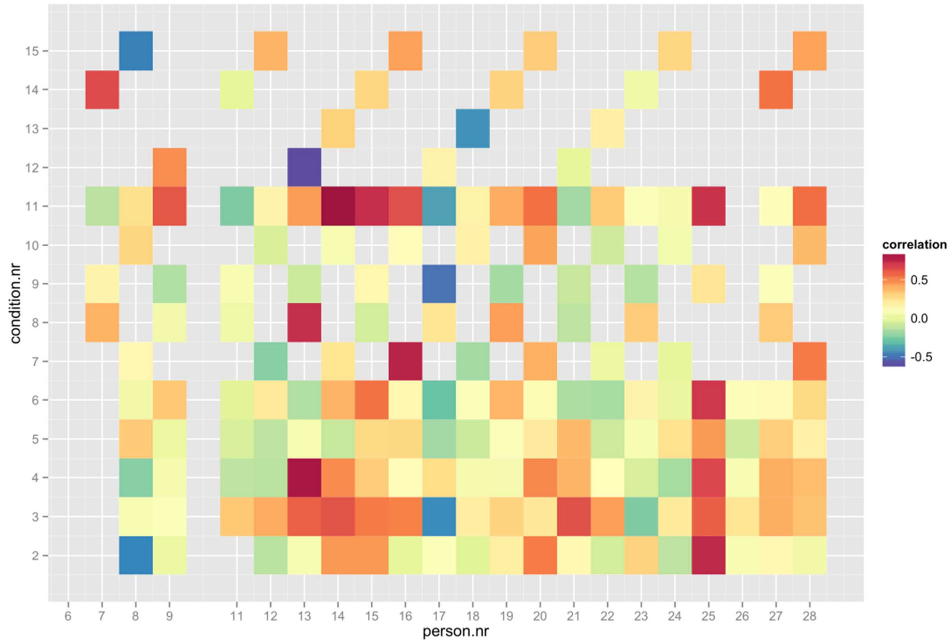


Figure 3.21 Correlation of measurements of Microsoft band and Mio band, for each participant, for each condition.

Furthermore, we looked into some of the extremes in more detail. Figure 3.22 shows a case of a high positive correlation (0.85) while Figure 3.23 shows the opposite: a correlation of -0.60 between the two smart bands. Again, this confirms that the (mal)functioning of the bands varies from situation to situation and that these tools for measuring heart rate under these conditions are not reliable.

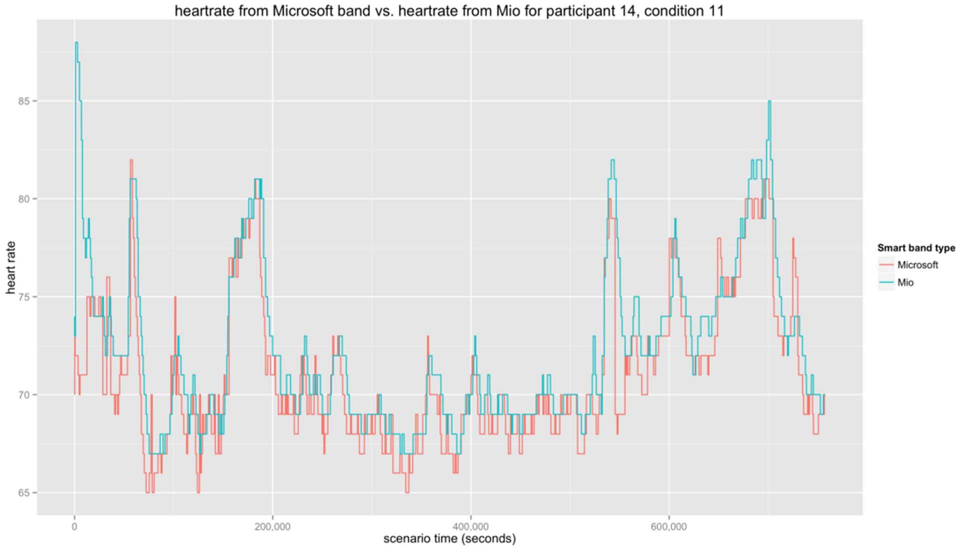


Figure 3.22 Positive correlation between measurements of the smart bands

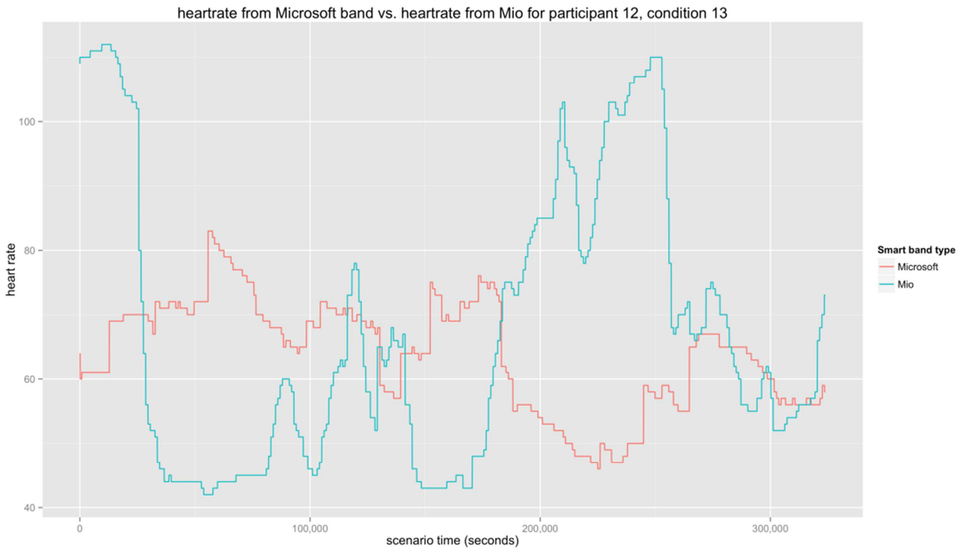


Figure 3.23 Negative correlation between measurements of the smart bands

In the experiment, the idea was to see whether heart rate during one minute before the TOC request was correlated to the actual response time to this signal.
Our hypothesis was that this heart rate correlates with the reaction time: high heart rates may indicate higher alertness, and therefore lower reaction time, and low heart rates may indicate a more restful state of the participant and therefore higher response times. However, since the heart rate data are highly unreliable, it was impossible to perform these analyses. A traditional heart rate monitor with ECG as a ground truth measure would be required for further research.

3.4.1 Smart band data: movement and steering wheel position

In addition to the participant's heart rate, the Microsoft band also measures acceleration in x, y, and z direction (Figure 3.24 and the yaw, pitch, and roll (axial velocity around z, y, and x axis, respectively, see Figure 3.25).

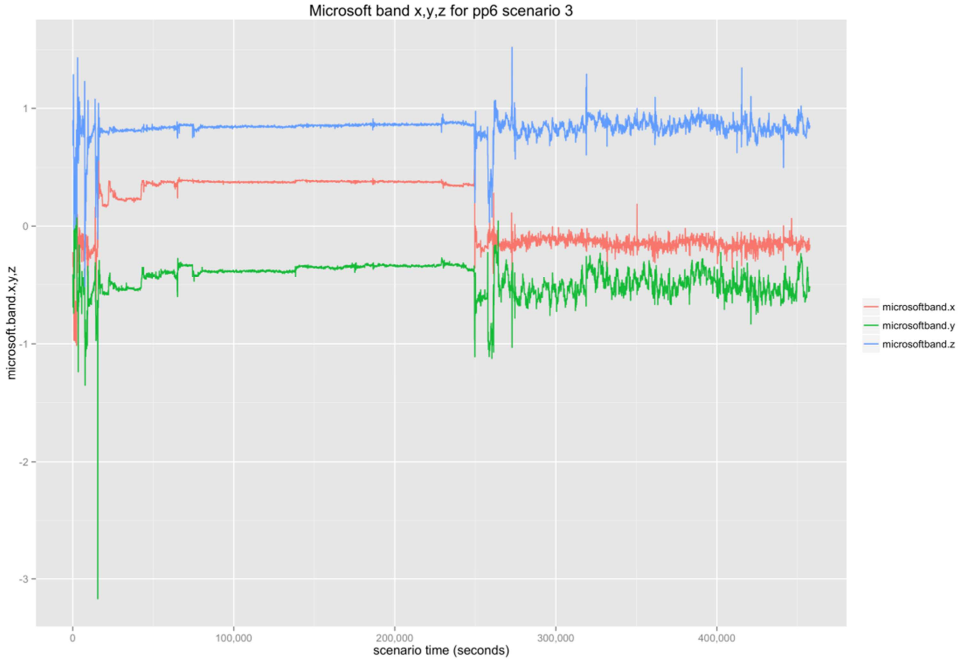


Figure 3.24 Acceleration measurements in x, y, and z direction of the Microsoft band

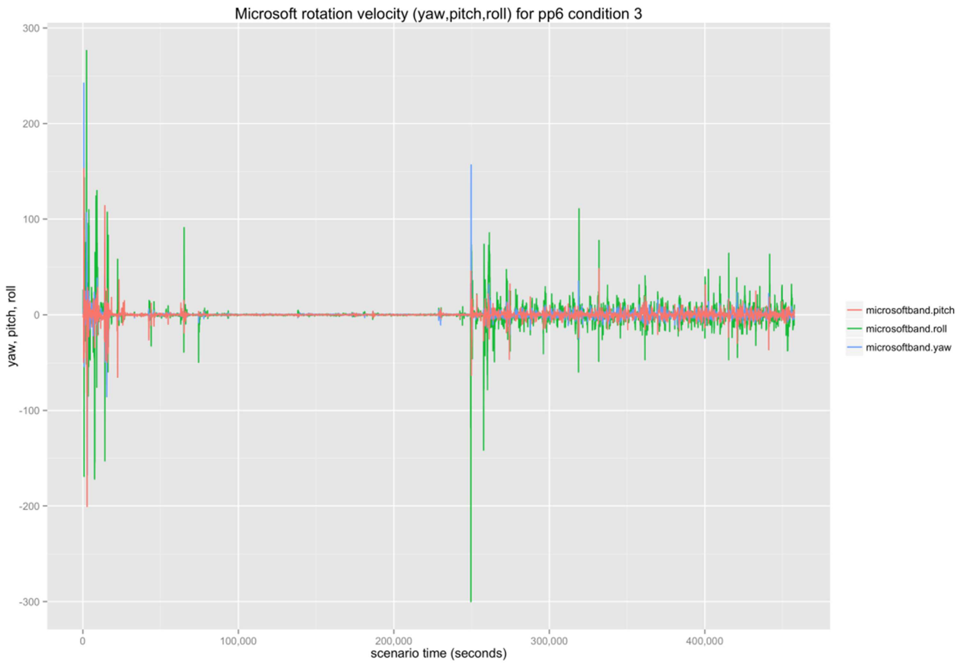


Figure 3.25 Yaw, pitch, and roll as measured by the Microsoft band

These figures suggest that movement measurements possibly may be used to conclude whether the participant has their hands on the wheel or not. Which in turn can be a measurement for the participant's performance. This does not hold for the steering wheel angle: Figure 3.26 shows that there is no correlation between any of the acceleration values and the steering wheel angle. The same holds for yaw, pitch, and role.

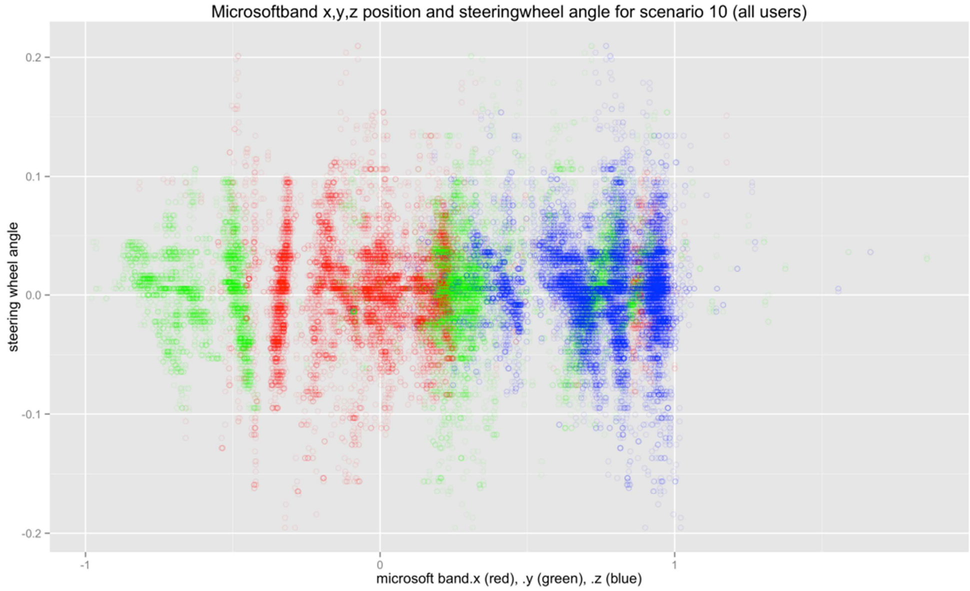


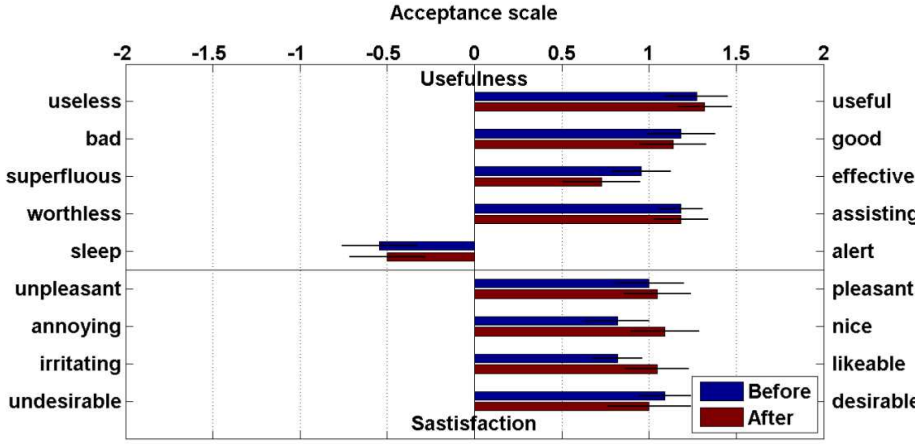
Figure 3.26 Scatterplot of acceleration in x,y, and z direction versus the steering wheel angle.

This means that more validation data based on the video images will need to be done before the direct measures of these wrist bands can be used for the interpretation of the data.

3.5 Questionnaires

Acceptance scale

The acceptance scale showed no significant differences for the usefulness or satisfaction scale when ratings before/after the experiment were compared (Figure 3.27). Overall, participants were positive about the usefulness and satisfaction both before and after experiencing the system. However, a potential issue for acceptance of the system is indicated by the participants both before and after the experiment; they perceive the system as moderately sleep inducing.



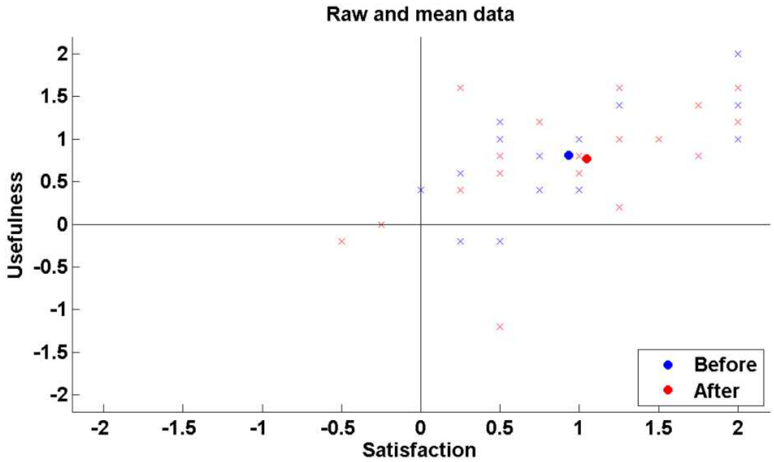


Figure 3.27 Acceptance scale before and after the experiment. Bar plots are averages with standard errors. Crosses mark scores of individual participants and the dots mark group averages.

RSME

The rating scale of mental effort showed that on average the participants rated the baseline driving as "somewhat effortful" compared to automated driving (Figure 3.28). RSME scale difference between automated driving and the manual period after the button press when they drove manually was significant (t(21)=-4,5, p<.001). They rated manual driving as more effortful compared to automated driving. However, the ratings after platooning were still lower compared to manual driving. There does not seem to be a negative after-effect of platooning.

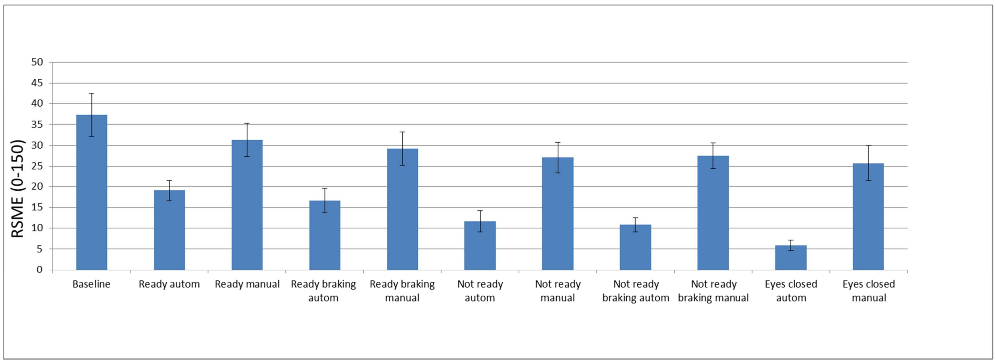


Figure 3.28 Mean rating scale of mental effort (1-150) per run of platooning ('autom') and the manual ('manual') period after the button press (vertical bars indicate S.E.).

Trust in the system

When the participants were asked if they would trust the automated driving system for real road driving conditions on the road, their responses did not significantly change before compared to after the experiment. Trust in the automated driving system in the simulator was higher before the experiment compared to on the road automated driving [F(1,42)=17.8; p<.001] (Figure 3.29). Trust in the system for use in real driving situations had in fact exactly the same mean before and after the experiment.

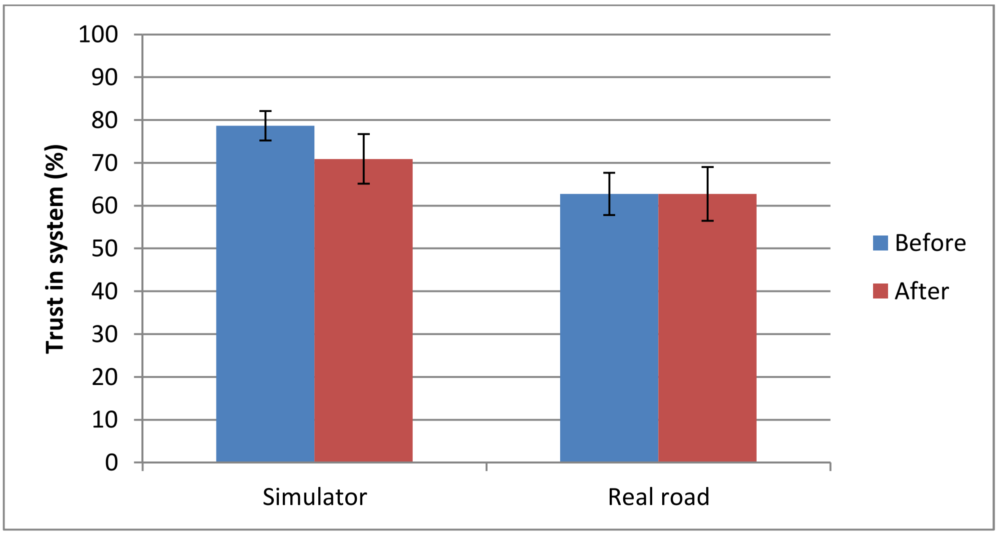


Figure 3.29 Trust in the a-VTB system for driving in the simulator and real road driving (0-100%); before and after the experiment.

Additional questions

Participants graded the system, after the entire experiment, a 7.25 (S.E.= 1.16) on a 10-point scale.

55% of the participants indicated that they would like to have the system in their own truck. 45% would not like to have the system in their truck.

3.6 Situational Awareness

During the different runs, participants were confronted with some salient vehicles along the side of the road (ambulance, broken-down vehicle on emergency lane). In the questionnaires at the end of the experiment, drivers were asked to indicate whether they remembered seeing these vehicles, and if so at what level of certainty (Table 3.1). The results are shown in Figure 3.30. Only for the Ready conditions more than 50% of the participants actually remembered correctly. During the Not ready and Eyes closed conditions the percentage of participants that remembered seeing the vehicles dropped. The four control items that were added to the questionnaire (they were not present in any of the runs) were “reported seeing” by 13,6% of the participants. Since there were 10 items to choose from, there was a 10% change of guessing it right.

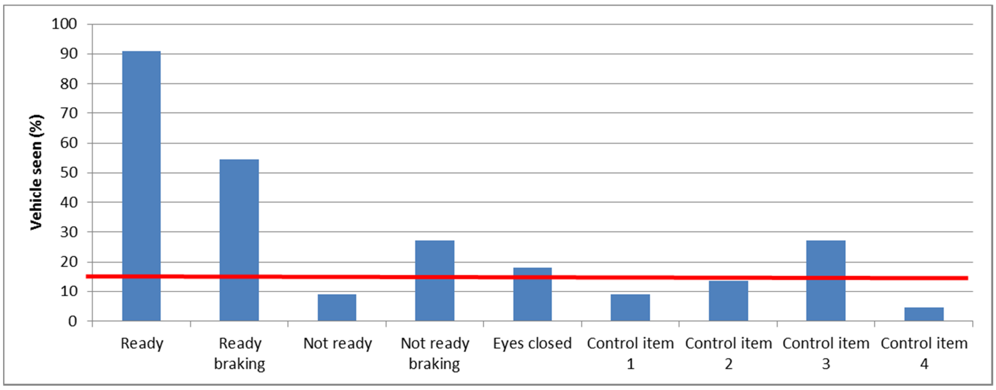


Figure 3.30 Correctly reported percentage (100% indicating 100% correct) for the vehicles that were presented on the side of the road and 4 control items. Red line indicates the average percentage of reporting of the control items (13,6%), which should have been 0%.

Table 3.1 Percentage and number of participants that have seen a vehicle per condition. And their reported certainty of seeing the vehicle (0-100%).

Condition	Seen (%)	Participants (#)	Certainty seeing vehicle (%)
Ready	90,9	20/22	100
Ready braking	54,5	12/22	90
Not ready	9,0	2/22	100
Not ready braking	27,2	6/22	86
Eyes closed	18,1	4/22	82
Control item 1	9,0	2/22	100
Control item 2	13,6	3/22	70
Control item 3	27,3	6/22	66
Control item 4	4,5	1/22	100

4 Discussion and conclusions

In the 2015 ERP truck driving simulator experiment, the primary interest was to see whether truck drivers who were requested to actively monitor the surroundings while the truck was in automated mode would respond differently to take-over requests, would show a different driving performance after the take-over situation and would be more aware of their surroundings than drivers that would either interact with an iPad or would have their eyes closed. Moreover, the generated data is to be used in data mining / machine learning strategies to investigate whether the readiness of the driver could be deduced from the installed sensors.

4.1 Take-over time in normal conditions

In 3 conditions, drivers were asked to take over the control of the truck in normal operations (no emergency situations). This means that after drivers pressed the button they were ready to take back control, the only driving task they had to perform was to keep the truck in the lane (steering behaviour on operational level) and press the gas pedal (longitudinal control on operational level). These are the most easy driving conditions, asking for the most simple take-over a truck driver could be confronted with.

The results showed that a driver being instructed to monitor the surroundings while in truck platooning (also called virtual tow bar) mode had shorter take-over times than when drivers an iPad or had their eyes closed during platooning. Remember that in this study, drivers could indicate themselves whether they were ready to take back control, so they could take more or less time. This may imply that the drivers took more time before requesting the control back, probably since they were aware that they had been out of the loop for a while. Since we also found larger response times in the eyes closed condition, the additional response times cannot only be attributed to the fact that these drivers had to put down the iPad before taking over control. On average drivers may take more than twice the time to indicate that they are ready to take back control as compared to conditions in which they were asked to stay attentive. When looking at individual response times, it may be up to 4 times as much.

However, there were large individual difference between drivers, with large differences within one condition between drivers, but also with large differences within drivers between the different conditions. As we can see from current data, it is not the case that all drivers responded slower in the iPad (Not ready) condition and even slower in the eyes closed condition. The variability in response times, however, was smallest for the condition in which drivers were monitoring the surroundings and largest for the eyes closed condition. The minimum and the maximum response time for the different conditions was 1.75 – 3.8 seconds for the Ready condition, 3.07 – 8.54 seconds for the Not ready condition and 2.33 -16.79 seconds for the eyes closed condition. Interestingly, when we look at the response times at the braking events (note that drivers did not know the braking events would be presented at the time they pressed the button), we see response times of 1.36 to 4.34 s. for the Ready condition and response times between 2.55 and 7.63 s. for the Not ready condition.

The voluntary take over times show a similar pattern when we provide drivers with a transition in which the truck automatically increases the headway after the take-over request, with higher response times for the Not Ready condition compared to the Ready condition. However the take-over times in the Not Ready condition with a transition are higher than in the Ready condition, with times varying from 1.58 to 5.13 s. in the Ready condition to 4.13 and 14.16 s. in the Not Ready condition. This is interesting since the headways are shorter than in the other conditions, so we expected take-over times to be longer compared to the normal (non-transition) conditions. However, this is not always the case.

The large variability in response times is probably also due to the individual differences in body, hand and feet position, and in the fact that people were holding a tablet, were sometimes wearing reading glasses or changed the seating position of their chair. This is behaviour we could see on the video images, and more detailed analyses of the video images will be done in order to find further explanatory variables for differences in response times.

4.2 Quality of driving performance in normal conditions

The behaviour after getting back control could be an indication for the quality of the take-over. In order words, are drivers indeed ready to take back control when they indicate they are. Hence different driving data from the phase after taking back control were analysed.

Two situations are distinguished: normal transitions (just taking over lateral and longitudinal control, but no specific actions are required) and more urgent situations (in which the lead truck would brake 3 seconds after participants got back the control). The braking conditions will be discussed separately.

In general we see that the driving speed after the take-over is independent of whether one had been monitoring the platooning, had been working with the iPad or had had their eyes closed. The standard deviation of speed was somewhat higher for the Not ready condition compared to the Ready condition, although differences are small.

The minimum time headway in the 10 seconds after take-over showed very small differences, but a significantly lower minimum time headway for manual driving compared to the Eyes Closed condition. This difference disappears when more time has passed after the transition.

In the lateral control, we see a higher standard deviation of lateral position (more swerving in the lane) for the condition in which a driver used the iPad before take-over compared to the situation in which one had been monitoring the surroundings while platooning. This means there is an indication towards lower lane keeping performance after having used the iPad. The strange thing, however, is that this difference is present if we analyse the 45 seconds after take over, but it is not present 10 seconds after take over. It seems that this appears somewhat longer after the transition. However, there may also be a link with road curvature. Even though there were no sharp curves in the experiment, the point at which drivers got back control was a little different for all drivers (some needed more and some took less time) which may have specifically influenced steering performance.

This will need to be standardised in future experiments, although we do not believe that overall this large biases.

In terms of steering behaviour, we found significantly higher steering reversal rates after the take-over for the condition in which one had been working with the iPad (Nor ready condition) before take-over compared to having had their eyes closed. Again, this effect disappears when we only analyse 10 seconds after the take-over. This may be related to the effect on SD lateral position, but is somewhat counterintuitive. Normally if drivers put more effort in steering, the swerving in the lane is expected to be lower. So in this case more active steering reversals with a higher swerving behaviour may be indicative for either poorer steering behaviour (more active steering without more accurate lateral position) or by drivers checking the response from the vehicle in order to actually make sure they are the ones steering (this result has been found in another TNO platooning study as well [Willemsen, Stuiver & Hogema, 2014], although this does not explain the absence of this effect in the Eyes Closed condition). When we link these steering data to the minimum time to line crossing (an indication for how close someone was to crossing a lane marking), we see that after having monitored the surroundings, the time to line crossing seems somewhat higher (safer) than after working with an iPad or having the eyes closed, but only somewhat longer after the transition. This effect does not seem to be present closer to the actual transition itself. In terms of lane exceedance, no differences were found either.

4.3 Quality of driving performance for braking conditions

Compared to manual driving, the Ready and Not ready condition had shorter response times to the braking lead truck. There was no difference in brake response time between the Ready and the Not ready condition. This indicates that, when required, drivers are as fast to respond irrespective of whether they had monitored the surroundings before the transition or had been interacting with the iPad. Also, the variance in response time is lower for the platooning conditions compared to manual driving. However, this does not mean that the situation after platooning was less critical than in the manual driving condition. The longer response times under manual driving conditions may be the result from this condition having longer time headways before the brake event, making this a far less urgent brake response. The minimum time headways during the brake events were significantly lower for the Ready and the Not Ready condition compared to manual driving.

The mean speeds after the take-over for the braking event are lower for the Ready and the Not ready condition compared to the braking event in the manual driving condition. This can be explained by the mere fact that driving speeds were already lower in the automated driving condition. There was no difference between the Ready and the Not ready condition in mean speeds. The standard deviation in speed was higher for the Ready and Not ready condition compared to the control condition.

When we look at the minimum Time-To-Collision (TTC) in the brake event, the values were significantly lower for the Ready and Not ready condition compared to manual driving. However there was no difference between the two platooning situations.

In terms of lateral performance, there was no difference in standard deviation lateral position between the conditions in the brake events, even though there was more strenuous steering behaviour in the manual driving condition in the brake event. However, the minimum time to line crossing for the Not ready condition in the brake event seemed a little bit higher (safer) than the Ready condition. When we analyse a shorter time period just around the braking event, no differences are seen.
When we look at actual lane exceedances, we see a similar pattern, with somewhat lower number of lane exceedance after having worked with an iPad, but this does not seem to be shown directly around the transition itself.

4.4 Physiological data

Unfortunately, the data from wristbands that we used were not reliable enough to measure heart rate during the driving task.. Therefore heart rate or heart rate variability could not be used as a predicting variable. Also, the accelerometers were not accurate enough to register actual movements from the hand to the steering wheel.

The eye movement data and fixation data also need to be checked by means of manual analyses, so they will be reported in the follow-up report of 2016.

4.5 Automated video analyses

The data from the hand and feet position were analysed by means of pattern recognition developed at TNO. Although the automated video analyses showed potential, the current software still needed to be adjusted to have 100% reliable results. Further checks with manual analyses will be performed in 2016.

4.6 Subjective data, workload and situational awareness

Subjective data showed a relatively good acceptance of and trust in the system for the participants, although participants indicated to have more trust in the system in simulated conditions than in real driving conditions. Automated driving was perceived as less effortful than manual driving. Potential issues for situational awareness were indicated for the Not ready condition where participants were unaware of a vehicle standing on the emergency lane, which is the direct result of participants not scanning the surroundings. Despite the fact that we confronted drivers with critical situations right after take-over, 60% of the participants indicated they wanted to have this system in their truck.

4.7 Conclusion

The aim of this study was to investigate how long it takes before truck drivers take back manual control after a system warning if they can choose their own moment of getting back control.

This study showed that there are indeed quite substantial differences in response times between conditions of platooning and furthermore there is much variability in response between various drivers. The largest effect on response time seems to be whether a driver is instructed to monitor the surroundings during the platooning.

Here response times are rather short and variability in response times is low. However, the fact that drivers took more time in the condition where they had been out of the loop (either working on an iPad or having their eyes closed), may also indicate that truck drivers are aware of possible risks and want to make sure that when they take back the control they are aware of their surroundings first.
Since this is the situation that future truck platooning concepts aim for, we need to take these varying and larger response times into account in the platooning concept. Interesting is the fact that some of the fast response times are similar to the condition where drivers monitored the surroundings, so some drivers under some conditions took back control very quickly, even after having been out of the loop.

This study therefore showed that there is much more to response times than just being in or out of the loop. When watching the videos that were logged during these drives, we found that drivers showed very different behaviour during platooning, having different positions of the iPad, some choosing a different seating position when having their eyes closed, some people looked outside but only in a very passive way, some people had to put their glasses on and off when interacting with the iPad, so there was a large variance in behaviour that may have caused the actual difference in response time.

Overall it seems that professional truck drivers do have quite a good idea of when they are ready to take back control. Indeed they take more time after having been out of the loop to actually take back control. But when they do take back control, they seem to be ready for normal operation of the truck and are also able to respond rather well to mildly critical (longitudinal) events. A next step would be to be able to predict how much time they would need to take back control. If this could be estimated, this could be used as input for providing a timely warning.

For future studies, more detailed analyses of the activity patterns during platooning would be of extreme interest, since they may be the explanatory factors in actual response times. By analysing the videos and analysing hand and feet position, hand position, eye movement behaviour and other variables, we will find data to put into our Driver Readiness Prediction Model. Besides this, it would also be interesting for future studies to see if drivers would also be ready to respond to highly critical events and near collisions after having used tablets or after having the eyes closed. In the current experiment, it seems that drivers only take back control if they are ready to actually do this, but this was not tested with being out of the loop in highly critical events. Also, the effect of time out of the loop would be important to study in order to develop SAE level 4 types of platooning concepts.

5 References

Laan, van der, J. D., Heino, A., & De Waard, D. (1997). A simple procedure for the assessment of acceptance of advanced transport telematics. Transportation Research - Part C: Emerging Technologies, 5, 1-10.

Ploeg, J., Van de Wouw, N. & Nijmeijer, N. (2014), Lp string stability of cascaded systems: Application to vehicle platooning. IEEE Transactions on Control Systems Technology. Accepted. available: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=06515636

Van der Horst, A.R.A. & Hogema, J.H. (2011), “Driving simulator research on safe highway design and operation. Transportation Research Record”, (2248), pp. 87-95.

Veltman, J. A., Gaillard, A.W.K. (1998). Physiological workload reactions to increasing levels oftask difficulty. *Ergonomics, 41*(5), 656-669.

Willemsen, D., Stuiver, A. & Hogema, J. (2914). Automated Driving Functions giving Control back to the Driver: A Simulator Study on Driver Dependent Strategies. Proceedings of the 5th International Conference on Applied Human Factors and Ergonomics, paper number 15-0109. Kraków, Poland.

Wilschut, E.S., Dufils, J.J & Willemsen, D.M.C. (2015). Drivers’ reactions to a failing automated two-truck platoon system. TNO report, Soesterberg, the Netherlands.

Zijlstra, F. R. H. 1993, Efficiency in work behaviour. A design approach for modern tools. Delft: Delft University Press.

A Overview driving data analysis

This appendix gives an overview of the driving data analysis as presented in Chapter 3.

	braking front vehicle				no braking front vehicle				All (braking / no braking irrelevant)			
	baseline	ready	not-ready	eyes-closed	baseline	ready	not-ready	eyes-closed	baseline	ready	not-ready	eyes-closed
indicator												
button response time										faster		
v_mean(45)	higher											
v_mean(10)	higher											
v_std(45)		higher	higher				higher					
v_std(10)		higher	higher				higher	higher				
brake response time		shorter	shorter									
THW(-10)	longer											
THW_min(45)												
THW_min(10)	longer							longer				
TTC_min(45)		shorter	shorter									
TTC_min(10)		shorter	shorter									
LatPos_std(45)							higher					
LatPos_std(10)												
SRR(45)		higher	higher			higher						
SSR(10)	higher											
TLC_min(45)												
TLC_min(10)												
Lane exceed (45)			lower									
Lane exceed (10)												

stat. significant difference
no stat. significant difference
(x) = x seconds after Take Over Time
n/a not analysable (zero variance)

B Acceptance in English and Dutch

Acceptance scale in English and Dutch (adapted from Van der Laan, Heino & De Waard, 1997). For more information regarding the scoring: http://www.hfes-europe.org/accept/accept.htm

English version

1 Useful	|__|__|__|__|__|	Useless
2 Pleasant	|__|__|__|__|__|	Unpleasant
3 Bad	|__|__|__|__|__|	Good
4 Nice	|__|__|__|__|__|	Annoying
5 Effective	|__|__|__|__|__|	Superfluous
6 Irritating	|__|__|__|__|__|	Likeable
7 Assisting	|__|__|__|__|__|	Worthless
8 Undesirable	|__|__|__|__|__|	Desirable
9 Raising Alertness	|__|__|__|__|__|	Sleep-inducing

Dutch version

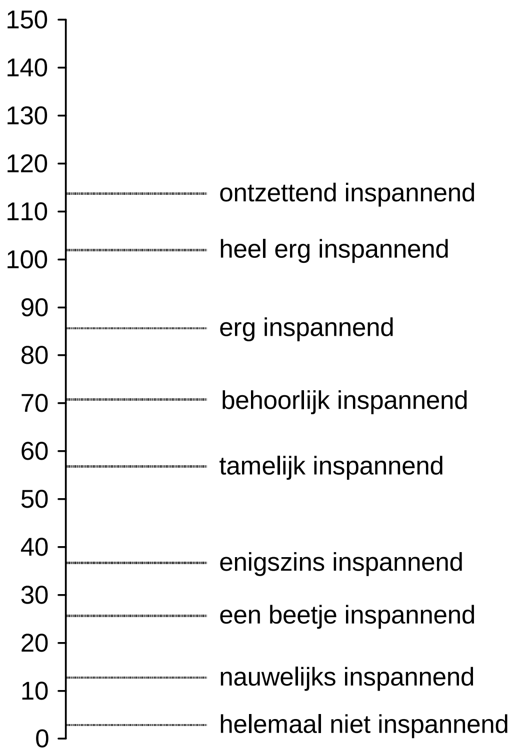
1 Nuttig	|__|__|__|__|__|	Zinloos
2 Plezierig	|__|__|__|__|__|	Onplezierig
3 Slecht	|__|__|__|__|__|	Goed
4 Leuk	|__|__|__|__|__|	Vervelend
5 Effectief	|__|__|__|__|__|	Onnodig
6 Irritant	|__|__|__|__|__|	Aangenaam
7 Behulpzaam	|__|__|__|__|__|	Waardeloos
8 Ongewenst	|__|__|__|__|__|	Gewenst
9 Waakzaamheidverhogend	|__|__|__|__|__|	Slaapverwekkend

C Rating scale of mental effort

The rating scale of mental effort (RSME; Zijlstra, 1993) in Dutch:
Beoordelingsschaal mentale inspanning (BSMI)

Inspanningsschaal BSMI

Wilt u door middel van het zetten van een kruisje op onderstaande lijn aangeven hoeveel inspanning het u gekost heeft om deze taak uit te voeren



Distribution list

Onderstaande TNO-medewerkers ontvangen een volledig exemplaar van het rapport in pdf-formaat.

D.J. de Cloe MSc.

Dr. D.M. Hoedemaeker

Ir. J.H. Hogema

Drs. M. Holewijn

S.G. Huveneers, MA.

Ir. S.H. Kalisvaart

Prof. Dr. M.H. Martens

Ir. R. Meijer

Prof. Dr. J.M.C. Schraagen

Ir. D.M.C. Willemsen

Dr. E.S. Wilschut

TNO Archief (locatie Soesterberg)