Empirical Longitudinal Driving Behaviour in case of Authority Transitions between Adaptive Cruise Control and Manual Driving

Silvia F. Varotto (corresponding author)
Department of Transport and Planning
Faculty of Civil Engineering and Geosciences
Delft University of Technology
Stevinweg 1, P.O. Box 5048, 2600 GA Delft, The Netherlands
Phone: +31 (0)15 2789575, Fax: +31 (0)15 2783179, Email: s.f.varotto@tudelft.nl

Raymond G. Hoogendoorn
Department of Transport and Planning
Faculty of Civil Engineering and Geosciences
Delft University of Technology
Stevinweg 1, P.O. Box 5048, 2600 GA Delft, The Netherlands
Phone: +31 (0)15 2784981, Fax: +31 (0)15 2783179, Email: r.g.hoogendoorn@tudelft.nl

Bart van Arem
Department of Transport and Planning
Faculty of Civil Engineering and Geosciences
Delft University of Technology
Stevinweg 1, P.O. Box 5048, 2600 GA Delft, The Netherlands
Phone: +31 (0)15 2786342, Fax: +31 (0)15 2783179, Email: b.vanarem@tudelft.nl

Serge P. Hoogendoorn
Department of Transport and Planning
Faculty of Civil Engineering and Geosciences
Delft University of Technology
Stevinweg 1, P.O. Box 5048, 2600 GA Delft, The Netherlands
Phone: +31 (0)15 2785475, Fax: +31 (0)15 2783179, Email: s.p.hoogendoorn@tudelft.nl

Word count:	
Abstract	249
Main text	4998
Figures	4 (1000)
Tables	3 (750)
Total	6997
References (n)	25

Submission Date: November, 15th 2014

ABSTRACT

Automated vehicles are expected to have a substantial impact on traffic flow efficiency, safety levels and levels of emissions. However, Fields Operational Tests suggest that drivers may prefer to disengage Adaptive Cruise Control (ACC) and resume manual control in dense traffic conditions and before performing manoeuvres such as lane changing. These so-called authority transitions can have substantial effects on traffic flow. To gain insight into these effects, a better understanding is needed of the relationships between these transitions, longitudinal dynamics of vehicles and behavioural adaptations of drivers.

In this context, a driving simulator experiment was set-up to gain insight into the effects of authority transitions between ACC and manual driving on longitudinal dynamics of vehicles. Participants were assigned to one of three conditions randomly. In the control condition, participants drove manually. In the first experimental condition, a sensor failure was simulated at a specific location after which drivers were expected to resume manual control. In the second experimental condition, drivers switched ACC off and on pressing a button whenever they desired.

Statistical tests indicate that the distributions of speed, acceleration and time headway significantly differ between the three conditions. In the first experimental condition, the speed drops after the sensor failure and the time headway increases after the discretionary re-activation of ACC. These results seem to be consistent with previous findings and suggest that authority transitions between ACC and manual driving influence significantly the longitudinal dynamics of vehicles, potentially mitigating the expected benefits of ACC on traffic flow efficiency.

Keywords: Authority transitions, Adaptive Cruise Control, driving simulator experiment, longitudinal driving behaviour.

INTRODUCTION

In recent years, interest in automated vehicles and systems supporting the drivers in their control task has increased. Automated vehicles are expected to have a significant impact on traffic flow efficiency, safety levels and the environment. These vehicles, in particular those that can show cooperative behaviour, are expected to reduce congestion levels because they will help to increase road capacity, anticipate traffic conditions downstream and increase the outflow from a queue [1].

The introduction of automated vehicles on public roads is likely to be gradual: the functionalities of automated systems are introduced through intermediate steps. SAE International [2] defines the different levels of automation as follows:

- Level 0: manual driving;
- Level 1: driving assistance;
- Level 2: partial automation;
- Level 3: conditional automation;
- Level 4: high automation;
- Level 5: full automation.

At the driving assistance level, the system takes over either the longitudinal or the lateral control. For example, Adaptive Cruise Control (ACC) is a driver assistance system providing support in longitudinal control through maintaining a desired speed and time headway. In partial automation, the system takes over longitudinal and lateral control, while the driver permanently monitors the system and is expected to resume control at any time. In conditional automation, the system takes over longitudinal and lateral control, while the driver does not have to continuously monitor the system and is expected to resume control in case of an emergency (e.g., sensor failure). In high automation, the system takes over longitudinal and lateral control, even if the driver does not respond adequately to a request to intervene in case of certain roadway and environmental conditions. In full automation, the system full-time takes over longitudinal and lateral control under all roadway and environmental conditions. The driver is not required to monitor the system.

Under certain traffic situations, however, drivers might disengage the automated system because they *prefer* to transfer to a lower level of automation (or manual driving) [3] or *are forced* to do so, for instance due to a sensor failure [4]. These transitions between different levels of automation are called *authority transitions*. These transitions can significantly affect the longitudinal and lateral dynamics of vehicles and are consequently expected to have a considerable impact on traffic flow efficiency (e.g., traffic flow stability).

To ex ante evaluate the impact of automated vehicles on traffic flow efficiency at varying penetration rates, mathematical models of driving behaviour of manually driven and automated vehicles can be implemented in microscopic simulation software packages [5, 6]. Currently, most mathematical models describing car-following and lane changing behaviour do not account for the possibility to switch the automated system on and off and are therefore not adequate in representing these transitions. Thus, an extension of these models is required. However, in order to do so, a better understanding is needed into how authority transitions affect the lateral and longitudinal dynamics of vehicles.

The aim of this research is to provide insight into the theory and empirics of longitudinal driving behaviour in case of authority transitions between ACC and manual driving. The main contribution of this paper is to explore the effects of authority transitions on longitudinal dynamics through extensive statistical analyses of data obtained through a driving simulator experiment. Participants were asked to drive in a vehicle equipped with ACC on a virtual two-lane highway using a medium fidelity fix-based driving simulator at Delft University of Technology. Speed, acceleration, distance and time headway, lateral position and lane changes were measured through registered behaviour. In a control condition, participants were required to drive manually. In the first experimental condition, a sensor failure was simulated at a specific location after which the driver was required to resume manual control over the vehicle. In the second experimental condition, the drivers were allowed to switch the system off and on voluntarily.

The paper is structured as follows. The next section reviews possible reasons for authority transitions. This section is followed by a description of the driving simulator experiment. Next, the results of the experiment are discussed in-depth through statistical analyses. The final section discusses the effects of authority transitions on longitudinal driving behaviour and presents the limitations of the proposed approach, while also suggesting recommendations for future research.

LITERATURE REVIEW

Before investigating the effects of authority transitions on longitudinal dynamics, it is essential to discuss the possible motivations that trigger the transitions. In this section, possible reasons for authority transitions between ACC and manual driving are proposed based on available literature. In order to explore the potential effects of the authority transitions on driving behaviour, we introduce an overview of the available research on behavioural adaptations and the changed role of the driver with ACC. After that, potentialities and limitations of data collection methods such as Field Operational Tests (FOTs) and driving simulator experiments are discussed.

Mandatory and discretionary authority transitions with ACC

The authority transitions appear to be strongly related to the characteristics of the driver support system. For example, FOTs [3] investigated driving behaviour with types of ACC systems that have limited decelerations capabilities and are inactive at speed below 30 km/h. Drivers prefer to disengage ACC and resume manual control during dense traffic conditions in order to have smaller distance headways. In medium – dense traffic conditions, drivers tend to deactivate the system to have full control of the vehicle (e.g., in case of overtaking manoeuver).

Discretionary authority transitions are defined as situations in which drivers disengage the automated system voluntarily. The most common motivations to initiate a discretionary authority transition with the above-mentioned types of ACC are presented below [5, 7, 8]:

- *Speed adaptation prior to a lane change manoeuver:* the driver plans to make a lane change and the current acceleration is not adequate;
- *Overruling due to defensive or offensive behaviour:* the driver brakes (or accelerates) to create a sufficient (or insufficient) gap for a vehicle in an adjacent lane for merging;
- *Left-lane speed adaptation*: the driver brakes to avoid illegal overtaking on the right and to adapt to the speed of the vehicle in the adjacent lane.

The authority transitions are defined as *mandatory* when drivers are forced to switch off by the system because of the functioning of the driver support system. Possible reasons for mandatory authority transitions with the above-mentioned types of ACC are presented below [5, 7, 8]:

- *A sensor failure:* the sensor cannot work properly (e.g., poor visibility due to adverse weather conditions) and the driver has to resume manual control;
- *Reaching the system support constraints in a safety-critical situation:* the system support constraints in speed and acceleration are reached; however, the driver needs to exceed these limits in order to avoid collision or overtake.

Behavioural adaptations and changed role of the driver with ACC

Adaptations in driving behaviour are defined as the collection of behavioural aspects that arise following a change in road traffic [9]. For instance, the influence of ACC systems activated on the longitudinal driving behaviour of drivers has been extensively investigated since the 90s. Similarly, there has been an interest in Automated Highway System (AHS) which takes over the longitudinal control of vehicles driving in an automated lane.

Driving simulator studies have found that ACC systems lead to more collisions than unsupported driving, for instance when the drivers have to resume manual control because the deceleration is not sufficient to avoid collision while approaching a stationary queue [10] and the system fails accelerating unexpectedly towards the vehicle in front [11]. Recently, a driving simulator study pointed out that in case of deceleration failures with ACC the mean reaction time of drivers varies between 1.60 s and 2.26 s, depending on the magnitude of the deceleration failure, and concluded that humans are poor monitors of automation [12]. Driving simulator studies have investigated the transfer of control between the AHS and the driver of a vehicle entering and exiting an automated lane [13]. In the latter, drivers were warned 60 s in advance before exiting the automated lane and resuming manual control. The authors concluded that these transitions resulted in an unacceptable rate of incomplete lane changes and collisions. In addition, it appears that ACC systems, which automatically regulate the speed when the vehicle gets too close to the leader, result in higher speeds and shorter time headways when they are active [14, 15]. However, little attention has been paid to the influence of mandatory and discretionary authority transitions as defined above on the longitudinal dynamics of vehicles and the behavioural adaptations of drivers.

The effects of ACC on driving behaviour may be related to the changed role of the driver, who is transformed from a manual controller to a supervisor of the system [1]. Indeed, automated vehicles require drivers who are capable to resume control in case of authority transitions. Studies in the field of aviation have suggested that monitoring the system for long periods of time might increase the workload of the driver [16] which can result in a reduction in situation awareness and a failure in the detection of critical changes in the state of the system [17]. In addition, indirect adaptation effects may be due to over-reliance on the system, which is defined as the tendency of human supervisors to place too much trust in automated systems [18]. In the road transport field, similarly, some driving simulator studies have found a reduction in situation awareness [19] and very low levels of self-reported mental workload [20] while driving with ACC.

Data collection methods

The validity of data collected in a FOT can be considered relatively high while the level of controllability is limited [21]. Indeed, in a FOT it is not possible to present exactly the same conditions to all the participants and therefore precisely control for potential confounding variables. Vice-versa, driving simulators possess a high degree of controllability. Presenting exactly the same traffic flow and environmental conditions to all the participants, driving performances can be assessed objectively [22]. Since reality is represented virtually, driving simulator experiments can result in a reduction in validity. However, recent findings [23] suggest that driving simulator studies possess relative validity, which means that the observed behavioural response converge in the same direction but not with the same magnitude as in real life.

The studies found [3, 5, 7, 8] point out that drivers may prefer to disengage ACC and resume manual control for many traffic situations (e.g., dense traffic conditions, lane change manoeuver, gap creation, left-lane speed adaptation). Moreover, the system can switch off due to sensor failure or system support constraints reached. These studies were based on data collected in a FOT. In addition, ACC is assumed to reduce driver’s vigilance and situation awareness. Therefore, we may conclude that ACC can compromise driver’s ability to respond in case of emergency situations and sensor failure. Most of the studies on the changed role of the driver in relation to automation were performed using driving simulator studies or were conducted in the field of aviation. Based on current literature, we miss a driving simulator experiment analysing the influence of the above-defined mandatory and discretionary authority transitions on the longitudinal dynamics of vehicles and the behavioural adaptations of drivers. Given the importance of understanding this transitional process and its implications on driving behaviour, in this research we focus on acquiring such data.

RESEARCH METHOD

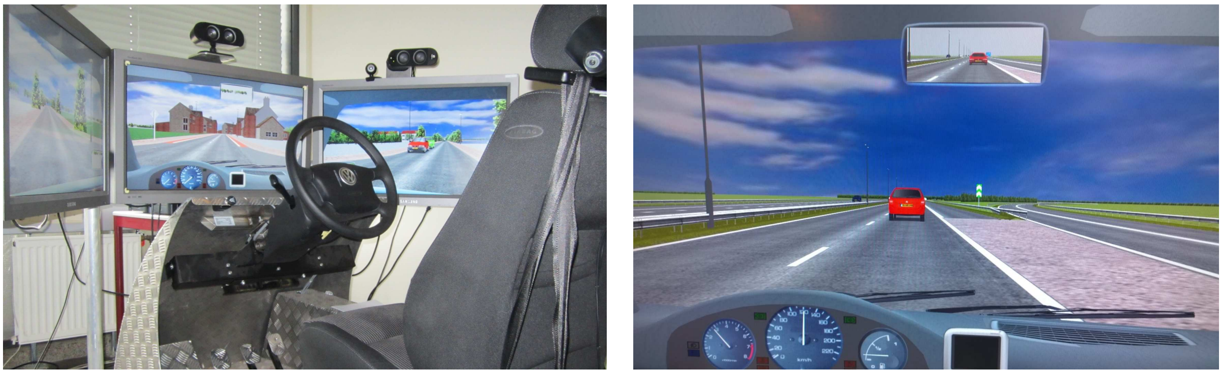
In this paper, we aim at gaining in-depth insight into driving behaviour during authority transitions through a driving simulator experiment. The main objective is to analyse to what extent authority transitions between ACC and manual driving affect the dynamics of vehicles. The behavioural assumption we would like to test is that the authority transitions between ACC and manual driving cause significant changes in speed, acceleration and time headway. In addition, we would like to explore the variations in the responses of drivers during mandatory and discretionary authority transitions. To study this, we use an experiment with a high degree of controllability.

In this section information is provided on the driving simulator as well as the driving environment designed for the purpose of this study. Next, the experimental design is discussed. In addition, the data collected to approximate the longitudinal driving behaviour and a description of the participants are provided.

The driving simulator and the driving environment

A medium-fidelity fixed-based driving simulator, which is displayed in Figure 1, was used in the experiments. This simulator was chosen because of availability reason. The simulator is composed of a steering wheel, pedals and gear stick which are obtained from a real car. Three screens which are placed at an angle of 120° show outside world images, the dash-board, the interior of the vehicle and the mirrors. The simulator provides a visual field of view of 180° horizontally and 45° vertically. The software was developed by StSoftware™ [24]. The gearbox was set to automatic.

For this experiment, we developed a driving environment composed of two main parts (7 km in total). The first part consisted of a test run (2 km) in an urban environment. In this phase, all the participants drove manually and the use of ACC was not possible. The aim was to accustom the participants to driving in the driving simulator as well as to check for simulator sickness. The second part, which is displayed in Figure 1, consisted of two segments (2 km each) of a virtual freeway with two lanes in each direction, connected by a one lane stretch (1 km). In this research, only the data collected in the two highway segments were analysed. The speed of the surrounding vehicles was programmed to vary randomly in the intervals (80, 85) and (110, 115) km/h in the left lane and (120, 125) km/h in the right lane. These vehicles changed lane when the speed of their leader was lower than their own speed. When ACC was switched on, the speed was set to 120 km/h (i.e., the speed limit) and the time headway was set to 1.5 s, without any possibilities to regulate the system settings.



(a) **(b)**

FIGURE 1 The medium-fidelity fixed-based driving simulator (a) and the driving simulation environment in the two-lane highway (b).

Experimental design

The experiment consisted of a control condition and two experimental conditions, making up a *complete three group independent samples randomized experimental design*. The driving environment and the characteristics of the surrounding vehicles were exactly the same for each condition. In the control condition (CC), authority transitions were not possible *by definition* and the participants had to drive manually. In the first experimental condition (EC1), ACC was switched on automatically after merging into the highway and the drivers were informed by a message on the screen (‘ACC is switched on’). On the second stretch of the highway, a sensor failure was simulated at a predefined location and the system automatically disengaged by decelerating the vehicle. The driver was warned by a message on the screen (‘Sensor failure!’) and was expected to resume manual control. At the next location, another message appeared on the screen (‘Sensors are ok!’) after which it was possible to switch on ACC again. In the second experimental condition (EC2), the drivers were allowed to switch ACC off and on by using a button on the dashboard discretionary.

Participants and data collection

The participants were assigned randomly to one of the above-mentioned groups. Seventy-five participants were recruited among the male and female inhabitants of Delft between the ages of 20 and 72 years old. A valid driving license and more than one year of driving experience were considered as a prerequisite.

Before the experiment, participants received written instructions on the general scope of the research, the features of the driving simulator and the potential risks related to simulator sickness. Participants were asked to drive as in real life and allowed to overtake. In addition, they were informed on the characteristics of the ACC available and warned to monitor the system and be able to resume manual control at any time. However, the precise scope of the experiment (i.e., analysing driving behaviour during authority transitions) was not communicated. After that, a written informed consent was signed. The whole procedure was executed following the regulations of the ethics committee of Delft University of Technology.

The duration of the experiment varied between 8 and 20 minutes, depending on the participants. After that, we asked to complete a questionnaire in which they reported demographic characteristics, driving experience, previous experience with cruise control and ACC in real life, information related to driving styles and mental workload experienced. Eight participants were not able to complete the experiment due to simulator sickness. Statistics regarding the characteristics of the participants who successfully completed the experiment are reported in Table 1. The analysis of the full questionnaire is not included due to space limitations. The two-sample Kolmogorov-Smirnov test is performed in order to determine whether the three groups come from the same population. The null hypothesis that the distributions of the variables gender, age and driving experience in the three groups come from the same distribution cannot be rejected at the 5% significance level. This means that the distributions of gender, age and driving experience do not differ significantly between the three groups. The test statistics are presented in Table 1.

Longitudinal driving behaviour was measured through registered data in the driving simulator. Speed, acceleration, distance and time headway, lateral position and lane changes were measured at a sampling rate of 10 Hz. Sixty-seven complete observations were collected and analysed in this paper.

TABLE 1 Statistics on the participants' characteristics in the Control Condition (CC), the Experimental Condition 1 (EC1) and the Experimental Condition 2 (EC2). *Female* is a variable which is equal to 1 when the participant is a female and 0 otherwise.

		CC		*EC1*		*EC2*
Participants (N)		25		21		21
Gender (n_{male}, n_{female})	14	11	15	6	12	9
Age (M_{years}, SD_{years})	47.08	14.75	38.10	11.52	39.19	12.86
Driving experience (M_{years}, SD_{years})	24.72	12.79	19.38	11.22	21.55	13.86

	Gender (female)			*Age (years)*			*Driving experience (years)*		
Two-sample Kolmogorov-Smirnov test	*CC EC1*	*CC EC2*	*EC1 EC2*	*CC EC1*	*CC EC2*	*EC1 EC2*	*CC EC1*	*CC EC2*	*EC1 EC2*
p-value	0.93	1.00	1.00	0.07	0.19	0.19	0.11	0.57	0.57
Test statistic	0.15	0.01	0.17	0.37	0.31	0.19	0.34	0.22	0.17

DATA ANALYSIS METHOD

The distributions of speed, acceleration and time headway are analysed in order to study the longitudinal dynamics of vehicles in case of authority transitions between ACC and manual driving. The behavioural hypothesis tested is that authority transitions between ACC and manual driving cause significant changes in speed, acceleration and time headway. After that, the characteristics of the mandatory and discretionary authority transitions in EC1 are investigated in terms of time needed to resume control and the consequent speed variation. Finally, a detailed analysis of the driving behaviour of two single drivers in EC1 is presented and discussed in-depth. Here, authority transitions are investigated by using a relative speed-spacing plane.

Analysis of speed, acceleration and time headway distributions

The outputs of the driving simulator are processed for each participant and the values of the variables speed, acceleration and time headway (rear bumper of the leader – front bumper of the follower) are calculated every two meters. For each location, the mean and the standard deviation of these variables are calculated between the participants in each condition. The distributions are plotted in Figure 2.

A one-sample Kolmogorov-Smirnov test is performed to check if the mean and standard deviation of the variables calculated as a function of distances in each condition are normally distributed. The null hypothesis that the distributions of the mean and standard deviation of speed, acceleration and time headway are normally distributed is rejected at the 5% significance level. After that, the two-sample Kolmogorov-Smirnov test is performed in order to understand if the mean and standard deviation of the variables are homogenous between the three groups. The null hypothesis that the mean and standard deviation of speed, acceleration and time headway in the three groups come from the same distribution is rejected at the 5% significance level. The p-value and the test statistic are reported in Table 2. The results indicate that the longitudinal dynamics of the vehicles differ significantly between the three conditions. The largest difference in speed and time headway can be found between the CC and the EC1.

Comparing the CC and the EC2 in Figure 2, the speed distributions seem to be similar in terms of mean and standard deviation. This result appears to be consistent with findings by Klunder et al. [5]. However, analysing the first segment of highway, in the CC the mean and the standard deviation are generally constant over the distances, while in the EC2 the mean speed increases progressively and the standard deviation decreases. These results seem to be consistent with the fact that more drivers switched on ACC over time. The distributions of the mean accelerations are similar in both segments. However, the possibility to switch ACC on and off discretionary can lead to higher variability between the drivers and therefore to a higher standard deviation. In the EC2, the mean and standard deviation of the time headway distribution are generally smaller and clearly decrease over distance in the first segment. This can be interpreted as an adaptation effect related to switching ACC on and off.

Comparing the EC1 to the CC and the EC2 in Figure 2, the use of ACC results in higher mean speeds and a lower standard deviation in the first segment where authority transitions are not possible. After the sensor failure, it is possible to note a significant drop in speed and increase in the standard deviation of speed, as a result of the different responses of drivers. A second drop in speed can be recognized after the message informing the drivers that ACC could be switched on again. Significant changes in mean values of acceleration can be noted corresponding to the aforementioned authority transitions. Small mean time headway can be observed in the first segment of the highway, while higher mean values can be found in the second segment. After sensor failure, indeed, the time headways increase, reaching values similar to these observed during manual driving. However, after the sensors are functioning again and thus it is possible to switch ACC on voluntary, higher time headways can be recognized. The latter result appears to be consistent with findings by Pauwelussen and Minderhoud [7] and Pauwelussen and Feenstra [8]. Higher time headways can potentially have a negative effect on traffic flow efficiency.

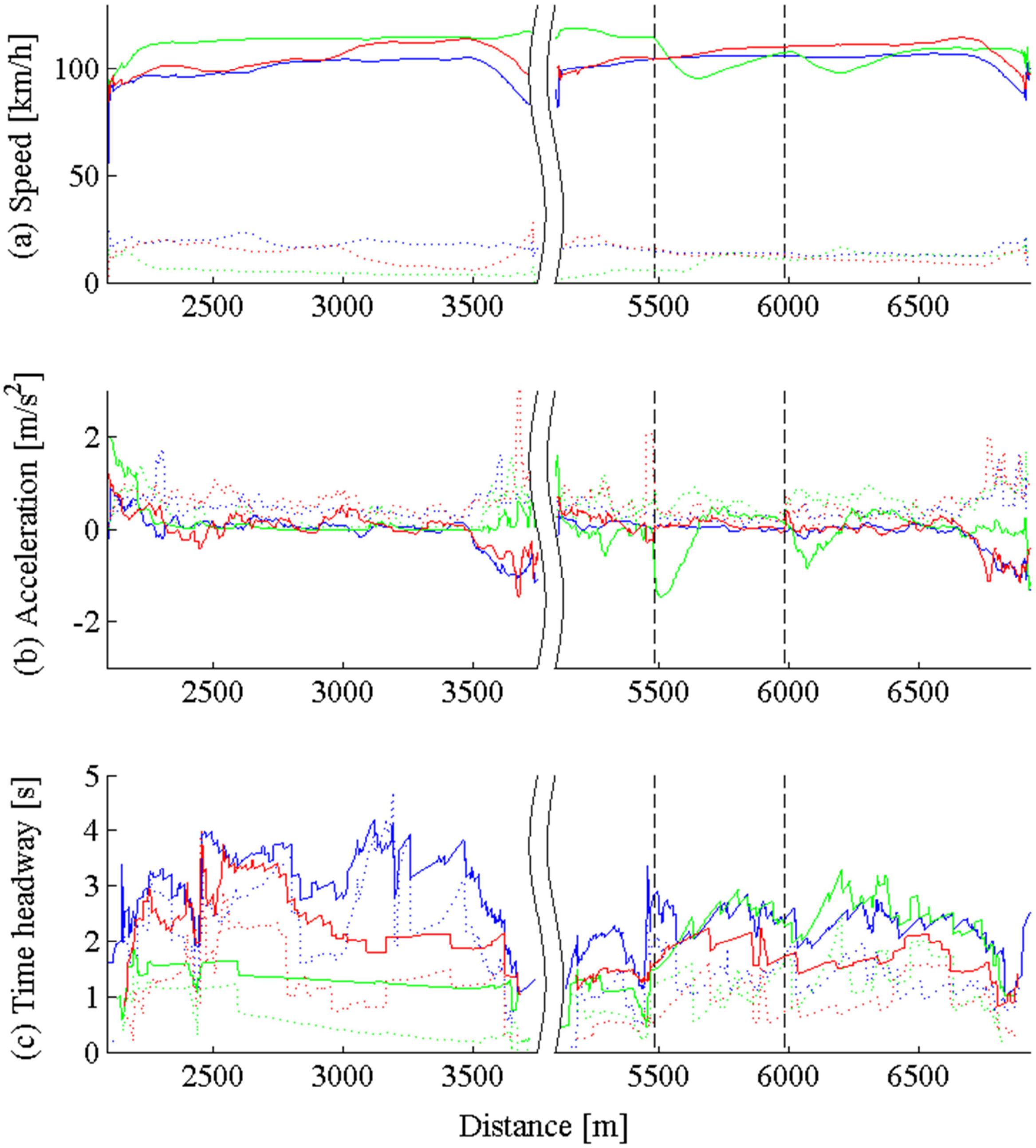


FIGURE 2 Mean (continuous line) and standard deviation (dashed line) of speed (a), acceleration (b) and time headway (c) distributions calculated as a function of the distance travelled since the beginning of the simulation for the Control Condition (blue), the Experimental Condition 1 (green) and the Experimental Condition 2 (red). The curve lines separate the first and the second segment of the highway. For each segment, drivers enter and exit the highway through on and off-ramps. The first dashed black line (distance= 5480 m) indicates the location where sensor failure is simulated. After sensor failure, drivers are expected to resume manual control. The second dashed black line (distance= 5981 m) indicates the location after which it was possible to switch on ACC again.

TABLE 2 Statistics on the speed, acceleration and time headway distributions calculated as a function of the distance travelled in the first and the second segment of highway for the Control Condition (CC), the Experimental Condition 1 (EC1) and the Experimental Condition 2 (EC2). In EC1, the sensor failure is simulated in the second segment of highway.

	Speed (km/h)			*Acceleration (m/s^2)*			*Time headway (s)*		
Mean of mean values over distances	*CC*	*EC1*	*EC2*	*CC*	*EC1*	*EC2*	*CC*	*EC1*	*EC2*
First segment	99.86	113.13	105.09	-0.02	0.16	0.03	3.07	1.30	2.36
Second segment	104.22	107.25	108.10	-0.06	-0.03	-0.01	2.21	2.10	1.66
Overall	102.15	110.05	106.67	-0.04	0.06	0.01	2.62	1.72	1.99
One-sample Kolmogorov-Smirnov test	*CC*	*EC1*	*EC2*	*CC*	*EC1*	*EC2*	*CC*	*EC1*	*EC2*
p-value	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Test statistic	1.00	1.00	1.00	0.35	0.32	0.30	0.88	0.80	0.85
Critical Value	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Two-sample Kolmogorov-Smirnov test	*CC* *EC1*	*CC* *EC2*	*EC1* *EC2*	*CC* *EC1*	*CC* *EC2*	*EC1* *EC2*	*CC* *EC1*	*CC* *EC2*	*EC1* *EC2*
p-value	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Test statistic	0.73	0.51	0.73	0.17	0.19	0.11	0.53	0.51	0.39
Mean of std. dev. values over distances	*CC*	*EC1*	*EC2*	*CC*	*EC1*	*EC2*	*CC*	*EC1*	*EC2*
First segment	18.59	5.28	13.65	0.50	0.31	0.62	2.43	0.60	1.38
Second segment	14.28	10.29	12.71	0.38	0.58	0.51	1.27	1.15	0.88
Overall	16.33	7.91	13.16	0.44	0.45	0.56	1.81	0.89	1.12
One-sample Kolmogorov-Smirnov test	*CC*	*EC1*	*EC2*	*CC*	*EC1*	*EC2*	*CC*	*EC1*	*EC2*
p-value	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Test statistic	1.00	0.98	1.00	0.55	0.51	0.54	0.76	0.57	0.61
Critical Value	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Two-sample Kolmogorov-Smirnov test	*CC* *EC1*	*CC* *EC2*	*EC1* *EC2*	*CC* *EC1*	*CC* *EC2*	*EC1* *EC2*	*CC* *EC1*	*CC* *EC2*	*EC1* *EC2*
p-value	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Test statistic	0.78	0.41	0.52	0.27	0.26	0.27	0.48	0.41	0.22

Analysis of authority transition in case of sensor failure (EC1)

In this section, the “time to resume control” and the “resulting speed variation” in case of authority transitions are analysed for each participant *n* in the EC1. The sensor failure triggers a mandatory authority transition between ACC and manual driving (i.e., mandatory switching off). After that, the possibility to reactivate ACC can lead to a discretionary authority transition between manual driving and ACC.

Mandatory switching off action

The time necessary to resume manual control $T_{RMC,n}$ in case of mandatory authority transitions is defined as the interval between the instant of sensor failure $T_{SFL,n}$ and the instant when the gas pedal is pressed again $T_{GPP,n}$. The distribution of $T_{RMC,n}$ is presented in Figure 3.

Assuming that T^* is the median value of $T_{RMC,n}$, the median of the speed variation distribution ΔV_n which occurs during the authority transition is calculated as follows in equation (1):

$$\Delta V = median\left(V_n^* - V_{SFL,n}\right), \tag{1}$$

Where

V_n^* is the speed at the instant T^* for each participant *n;*

$V_{SFL,n}$ is the speed at the instant of the sensor failure for each participant *n*.

Discretionary switching on action

The time necessary to resume automatic control $T_{RAC,n}$ in case of discretionary authority transition is defined as the interval between the instant when the sensors are functioning again $T_{SFC,n}$ and the instant when ACC is switched on again by pressing the button $T_{ACC\ ON,n}$. The distribution of $T_{RAC,n}$ is presented in Figure 3. Two participants did not switch ACC on after the sensors were functioning again.

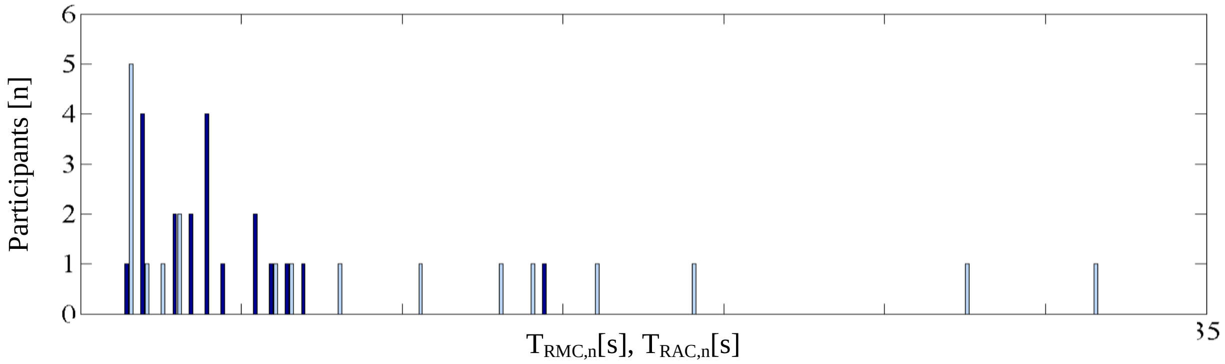


FIGURE 3 Time to resume manual control $T_{RMC,n}$ after sensor failure (blue) and time to resume automatic control $T_{RAC,n}$ after sensors are functioning again (light blue).

The speed variation distribution ΔV_n is calculated similarly as described in equation (1). Statistics on the speed variation ΔV_n, the time to resume manual control $T_{RMC,n}$ and automatic control $T_{RAC,n}$ are reported in Table 3.

TABLE 3 Statistics on the distributions of time to resume control and speed variation in case of authority transition

	Time to resume control (s)			*Speed variation (km/h)*		
EC1	*min*	*max*	*median*	*min*	*max*	*median*
Mandatory switching off	1.70	14.50	3.85	-20.37	-8.34	-18.18
Discretionary switching on	1.40	31.40	5.80	-26.00	5.42	-4.22

When observing the time to resume control, it can be pointed out that the minimum value is lower in case of discretionary switching on. However, the discretionary switching on results in a higher median value of time to resume control due to the larger variability in the response of drivers. It is interesting to note that in both cases the authority transitions result in a negative median speed variation, which can have considerable effects on traffic flow. The mandatory switching off always implies a negative speed variation while the discretionary switching on can lead to positive or negative speed variation, depending on the response of the drivers.

Analysis of longitudinal dynamics of single drivers (EC1)

In this section, the longitudinal dynamics of two individual drivers (driver-1 and driver-2) in EC1 are analysed in detail. The scope is to confirm and examine in-depth the general results found for the whole sample.

In Figure 4 (a) – (b) speed, acceleration and time headway distributions are calculated as a function of distance travelled since the beginning of the simulation. In addition, the relative speed $dv = v_{i-1} - v_i$ to the leader $i-1$ and the distance headway $s= x_{i-1} - x_i$ (rear bumper of the leader – front bumper of the follower) are calculated and plotted in a (dv, s) plane in Figure 4 (c) – (d). When no leader was present, the data were discarded. In these (dv, s) planes, four different phases are distinguished following the definitions proposed in the previous section:

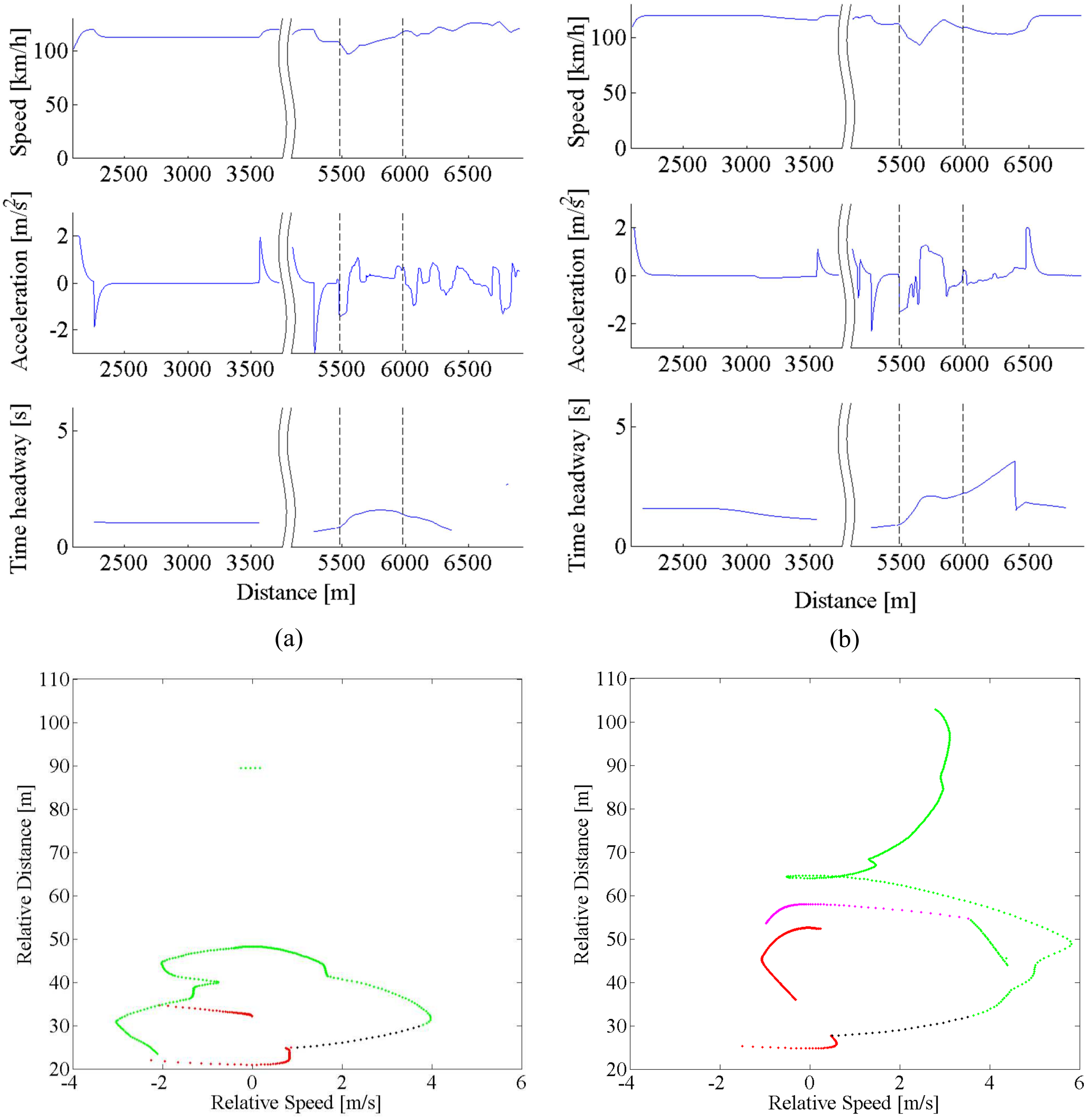
1. ACC before sensor failure (driver-1 and driver-2);
2. Authority transition after mandatory switching off (driver-1 and driver-2);
3. Manual driving after resuming control (driver-1 and driver-2);
4. ACC after discretionary switching on (driver-2).

Constant acceleration periods could be clearly recognized. The duration of these periods is not fixed but is related to the state of the follower in relation to the leader. It can be assumed that the transitions between the above-mentioned different phases correspond to an action of the follower who wants to increase or decrease the acceleration.

When driving with ACC, periods of constant relative distance can be identified. The system tends to reduce the relative speed to zero. Here, discontinuities in the plots correspond to changes in the leader and consequently rapid variations in the acceleration. After the sensor failure, the vehicles decelerate uniformly and the relative speeds increase, until the drivers resume control and start to press the gas pedal again.

When the vehicle is driven manually, an oscillation of the vehicle motion around states with a relative velocity equal to zero can be recognized [25]. It is interesting to note the same phenomenon cannot be identified during authority transitions and with ACC, which reacts to small speed differences.

Driver-1 did not switch on again ACC after resuming control. When driver-2 decided to switch on again ACC, the relative speed and distance headway increased compared to ACC before sensor failure, meaning that the gap to the leader increased in space and speed.



(a) (b)

(c) (d)

FIGURE 4 Speed, acceleration and time headway distributions calculated as a function of the distance travelled since the beginning of the simulation in the Experimental Condition 1 (EC1) for driver-1 (a) and driver-2 (b). The curve lines separate the first and the second segment of the highway. For each segment, drivers enter and exit the highway through on and off-ramps. The first dashed black line (distance= 5480 m) indicate the location where sensor failure is simulated. After sensor failure, drivers are expected to resume manual control. The second dashed black line (distance= 5981 m) indicates the location after which it was possible to switch on Adaptive Cruise Control (ACC) again. The *(dv, s)* planes in EC1 are reported for driver-1 (c) and driver-2 (d). Four phases are distinguished: ACC before sensor failure (red); authority transition after mandatory switching off (black); manual driving after resuming control (green); ACC after discretionary switching on and off (magenta). Each dot corresponds to a time step.

CONCLUSION AND FUTURE RESEARCH

The available literature indicates that drivers may prefer to disengage ACC and resume manual control in dense traffic conditions and to perform manoeuvres such as lane changing. Authority transitions can have significant effects on traffic flow. However, these studies rely on data collected in FOTs and thus little insight is available on the relationships between the mandatory and discretionary authority transitions identified, longitudinal dynamics of vehicles and behavioural adaptations of drivers.

In this paper, an in-depth insight is gained into the influence of these transitions between ACC and manual driving on longitudinal dynamics of vehicles. For this purpose, a driving simulator experiment was set-up. Participants were asked to drive a vehicle equipped with ACC on a virtual two-lane highway. In a control condition (CC), participants were required to drive manually. In the first experimental condition (EC1), a sensor failure was simulated at a specific location after which the driver was required to resume manual control. In the second experimental condition (EC2), the drivers were allowed to switch the system off and on voluntarily.

The distributions of speed, acceleration and time headway are analysed for each group. Statistical tests indicate that these variables significantly differ between the three conditions. Comparing the CC and the EC2, the speed distributions seem to be similar in terms of mean and standard deviation. Looking at the EC1, the use of ACC results in higher mean speeds and lower standard deviation in the first segment of the highway where authority transitions are not possible. After the sensor failure, it is important to note a significant drop in speed (ΔV=-18.18 km/h) and increase in the standard deviation of speed, following from the different responses of drivers. The median time to resume control after sensor failure is equal to 3.85 s. Notably, a similar speed drop is recognizable when the system can be voluntary switched on again (ΔV=-4.22 km/h). The median time before voluntary switching ACC on after the message is equal to 5.80 s. Small mean time headways (1.30 s) can be observed in the first segment of the highway, while higher mean values (2.10 s) can be found in the second segment where the sensor failure is simulated. Authority transitions seem to result in higher time headways than these observed when ACC is activated permanently.

The results suggest that authority transitions between ACC and manual driving have significant effects on the longitudinal dynamics of ACC vehicles that can lead to negative effects on traffic flow efficiency in mixed traffic condition, such as traffic flow instability, an increase in congestion levels and a slower clearance of congestion. In addition, these outcomes seem to be consistent with studies found in literature where data from FOT were analysed [3, 5, 7, 8]. Therefore, the assumed relative validity of driving simulator experiments [23] seems to be confirmed.

The driving simulator appears to be a useful instrument to do an in-depth investigation of the effects of authority transitions on longitudinal dynamics with a high level of controllability. However, further analysis is necessary to better understand the role of discretionary authority transitions and to validate the results obtained in the driving simulator experiment by using data from FOTs. A limitation of this study is that participants drove for a very short period of time and because of this, little insight is gained on the variations within drivers. In addition, these results are related to light traffic flow condition and cannot be directly generalized to dense traffic flow. Further research directions might be as follows. First, the analysis of driving behaviour could be extended to lateral dynamics. Second, more work is needed in order to assess the performances of current mathematical models during authority transitions. Third, new mathematical models which account for authority transitions should be developed and the effects on traffic flow should be investigated by using microscopic simulations. Fourth, the research could be extended to investigate authority transitions in case of partial and high automation.

ACKNOWLEDGMENTS

The research has been performed in the project HFAuto – Human Factors of Automated Driving (PITN-GA-2013-605817). The experimental set-up has been discussed during the First HFAuto project meeting (Delft, 2014). The work presented in this paper has greatly benefited from the comments of the participants. Special thanks to Miltos Kyriakidis for advice in the set-up of the data collection and Lin Xiao for assistance during the experiment at Delft University of Technology. The authors would like to thank Joost De Winter (Delft University of Technology) and four anonymous reviewers for their valuable comments which contributed to improve the quality of this paper.

REFERENCES

[1] Hoogendoorn, R. G., B. van Arem, and S. P. Hoogendoorn. Automated Driving, Traffic Flow Efficiency And Human Factors: A Literature Review. In *Annual Meeting of the Transportation Research Board*, Washington D. C., 2014.

[2] SAE International. *J3016 SAE – Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems*. 2014.

[3] Viti, F., S. P. Hoogendoorn, T. P. Alkim, and G. Bootsma. Driving behavior interaction with ACC: results from a Field Operational Test in the Netherlands. In *Intelligent Vehicles Symposium*, Eindhoven, 2008.

[4] Nilsson, J., N. Strand, and P. Falcone. Driver performance in the presence of adaptive cruise control related failures: Implications for safety analysis and fault tolerance. In *Annual IEEE/IFIP Conference on Dependable Systems and Networks Workshop*, 2013.

[5] Klunder, G., M. Li, and M. Minderhoud. Traffic Flow Impacts of Adaptive Cruise Control Deactivation and (Re)Activation with Cooperative Driver Behavior. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2129, 2009, pp. 145–151.

[6] Kesting, A. *Microscopic Modeling of Human and Automated Driving: Towards Traffic-Adaptive Cruise Control*. Saarbrücken: Verlag Dr. Müller, 2008.

[7] Pauwelussen, J., and M. Minderhoud. The Effects of Deactivation and (Re)activation of ACC on Driver Behaviour Analyzed in Real Traffic. In *IEEE Intelligent Vehicles Symposium*, Eindhoven, 2008.

[8] Pauwelussen, J., and P. J. Feenstra. Driver Behavior Analysis During ACC Activation and Deactivation in a Real Traffic Environment. *IEEE Transactions On Intelligent Transportation Systems*, Vol. 11, No. 2, 2010, pp. 320 – 338.

[9] Martens, M. H., and G. D. Jenssen. *Behavioral Adaptation and Acceptance*. London: Springer Verlag, 2012.

[10] Nilsson, L. Safety Effects of Adaptive Cruise Control in Critical Traffic Situations. In 2nd World Congress of Intelligent Transport Systems, Tokyo, 1995.

[11] Stanton, N. A., M. Young, and B. McCaulder. Drive-by-wire: The case of driver workload and reclaiming control with adaptive cruise control. Safety Science, Vol. 27, 1997, pp. 149-159.

[12] Strand, N., J. Nilsson, I. Karlsson, and L. Nilsson. Semi-automated versus highly automated driving in critical situations caused by automation failures. *Transportation Research Part F* (Forthcoming), 2014.

[13] Barfield, W., and T. A. Dingus. *Human Factors in Intelligent Transportation Systems*. New York: Psychology Press, 2014.

[14] Ward, N., S. Fairclough, and M. Humphreys. The Effect of Task Automatisation in Automotive Context, a Field Study of an AICC System. In *International Conference on Experimental Analysis and Measurement of Situation Awareness*, Florida, 1995.

[15] Dragutinovic, N., K. A. Brookhuis, M. P. Hagenzieker, and V. Marchau. Behavioural effects of Advanced Cruise Control Use – a meta-analytic approach. *European Journal of Transport and Infrastructure Research*, Vol. 5, No. 4, 2005, pp. 267-280.

[16] Parasuraman, R., M. Mouloua, and R. Molloy. Effects of adaptive task allocation on monitoring of automated systems. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, Vol. 38, No. 4, 1996, pp. 665-679.

[17] Ephrath, A. R., and L. R. Young. Monitoring vs. man-in-the-loop detection of aircraft control failures. In *Human detection and diagnosis of system failures,* Springer, 1981, pp. 143-154.

[18] Danaher, J. W. Human error in ATC system operations. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, Vol. 22, No. 5, 1980, pp. 535-545.

[19] Stanton, N. A., and M. Young. Driver behaviour with adaptive cruise control. *Ergonomics*, Vol. 49, 2005, pp. 1294-1313.

[20] Saffarian, M., R. Happee, and J. De Winter. Why do drivers maintain short headways in fog? A driving-simulator study evaluating feeling of risk and lateral control during automated and manual car following. *Ergonomics*, Vol. 55, 2012, pp. 971-985.

[21] Anund, A., and K. Kircher. *Advantages and disadvantages of different methods to evaluate sleepiness warning systems*. Swedish National Road and Transport Research Institute, Linköping, 2009.

[22] De Winter, J., P. Wieringa, J. Kuipers, M. Mulder, M. Van Paassen, and J. Dankelman. Driver assessment during self and forced-paced simulation-based training. In *Driving Simulation Conference Europe*, Paris, 2006.

[23] Yan, X., M. Abdel-Aty, E. Radwan, X. Wang, and P. Chilakapati. Validating a driving simulator using surrogate safety measures. *Accident Analysis & Prevention*, Vol. 40, No. 1, pp. 274–288, 2008.

[24] van Wolffelaar, P. C., and W. van Winsum. A new driving simulator including an interactive intelligent traffic environment. In *The 3rd International Conference on Vehicle Navigation and Information System*, 1992.

[25] Leutzbach, W. *An introduction to the theory of traffic flow*. Berlin: Springer-Verlag, 1988.