This article is the accepted author's manuscript of an article that was published in Transportation Research Part F: Traffic Psychology and Behavior. This version of the article does not include publisher value-added contributions such as copy-editing, formatting, technical enhancements and pagination. The final version of the article was published as:

Naujoks, F. & Totzke, I. (2014). Behavioral adaptation caused by predictive warning systems - The case of congestion tail warnings. *Transportation Research Part F, 26*, 49-61. doi:10.1016/j.trf.2014.06.010

Behavioral adaptation caused by predictive warning systems – the case of congestion tail warnings

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Abstract

Wireless communication technologies (e.g., C2X-communication or mobile telephony and broadcasting) make it possible to forewarn drivers of dangerous traffic situations. Using a motion-based driving simulator with N = 16 participants, it has already been possible to illustrate an increase in traffic safety based on early, precise congestion tail warnings on motorways (Totzke, Naujoks, Mühlbacher & Krüger, 2011). The paper at hand presents an additional evaluation of the study with regard to (negative) 'behavioral adaptation'; that is to say, non-intended changes in driving behavior based on the introduction of congestion tail warnings. As part of the above-mentioned study, older and younger participants drove through road sections with different traffic conditions (free flow vs. synchronized traffic) performing different test situations (approaching different congestion tails with vs. without assistance of the warning system). In order to investigate behavioral adaptation effects, drivers completed additional road sections in which congestion tail situations were possible, but did not occur. In these situations, an in-vehicle warning device displayed that a congestion tail warning was possible ('assistance possible') or not ('assistance not possible'). During test drives with potential assistance, negative behavioral adaptations can be found: (1) increase of maximum speed, (2) decrease of minimum time-to-collision (TTC_{min}) when following another vehicle in free flow traffic and (3) increased intensity of performing a secondary task compared to driving without assistance. The reduction in TTC_{min}-values applied in particular to older drivers, whereas an increased secondary task involvement was mainly found among younger drivers during synchronized traffic. The results indicate that the introduction of predictive warning systems may cause behavioral adaptations that may limit the intended safety effect of the warning system. With this in mind, it is advisable to include the assessment of (negative) behavioral adaptations into research concepts when evaluating predictive warning systems.

Keywords: *Behavioral Adaptations, C2X-Communication, Driving Simulation, Older Drivers*

1. Introduction

1.1 Motivation

Wireless communication technologies (e.g., C2X-communication or mobile telephony and broadcasting) provide the possibility of assisting drivers with predictive warnings in potentially dangerous driving situations. It has been shown repeatedly that predictive warning systems have the ability to enhance active driving safety (e.g., Lenné & Triggs, 2008; Mahr, Cao, Theune, Schwartz & Müller, 2010; Naujoks, Grattenthaler & Neukum, 2013; Naujoks & Neukum, 2014). However, the introduction of these forward-looking warning systems, as with Advanced Driver Assistant Systems (ADAS) in general (Brookhuis, De Waard & Janssen, 2001), may also lead to non-intended effects on driving behavior, e.g., increase of vehicle speed or decrease in following distance. Thus, their intended positive effects may not be realized or may not occur in their entirety (Martens & Jenssen, 2012). According to Marberger (2007), such unintended behavioral changes may be defined as so-called 'improper use' of driver assistance systems. From the perspective of product liability, a further distinction between so-called 'abuse' (willful contrary use), and 'incorrect use' (unintended misuse) is of importance (Gasser et al., 2012), as incorrect use caused by poor understanding of a system's performance and limitations could cause a driver assistance system to be 'defective' (van Wees & Brookhuis, 2005). In view of incorrect use, the goal of the present study was to assess non-intended behavioral changes caused by a predictive congestion-tail warning system. Although a growing body of research on the effectiveness of such congestion tail warnings exists, the topic of non-intended behavioral changes has been neglected in the published research about this new type of warning system.

1.2 Behavioral adaptations: Definition, explanatory models and empirical findings

It must be noted that the above-mentioned differentiation of 'abuse' and 'incorrect use' is not always clear from a practical point of view since the information provided by the manufacturers regarding intended use of an ADAS is sometimes ambiguous. Another issue is the difficulty to define what drivers are entitled to expect from the respective ADAS on the basis of objective standards (van Wees & Brookhuis, 2005). For this reason, during the empirical study of foreseeable misuse (Marberger, 2007), the focus was directed towards the concept of so-called negative 'behavioral adaptation' (OECD, 1990). Behavioral adaptations are not-intended changes in behavior of traffic participants after changes to the traffic system (OECD, 1990) and thus include both willful contrary use and unintended misuse:

> *“Behavioural adaptations are those behaviours which may occur following the introduction of changes to the road-vehicle-user system and which were not intended by the initiators of the change.“ (p.23).*

According to Martens and Jenssen (2012), the most prominent example of behavioral adaptation is the introduction of antilock braking systems (ABS): Sagberg, Fosser and Sætermo (1997) showed, that driving with ABS lead drivers to keep shorter following distances. The emergence of such negative behavioral adaptations has been described many times in traffic-psychological behavior models and has been illustrated in empirical studies (e.g., Forward Collision Warning (FCW) and Adaptive Cruise Control (ACC): Cotté, Meyer & Coughlin, 2001; Fancher et al., 1998; Hoedemaeker & Brookhuis, 1998; Janssen & Nilsson, 1993; Rudin-Brown & Parker, 2004; Ward, Fairclough & Humphreys, 1995). Explanatory models interpret these findings as:

- Adaptation to **risk perception** (e.g., Fuller, 1984; Näätänen & Summala, 1976; Wilde, 1988): Here, the assumption is made that during driving, drivers assess the perceived risk and compare it with their subjectively acceptable risk. A decrease of the perceived risk (e.g., by the introduction of safety measures) results in a discrepancy to the subjectively acceptable risk and the likelihood of discrepancy-reducing behavior (e.g., risky driving) increases. Thus, a rise in subjective safety after the introduction of a safety measure may lead to a riskier driving style.
- **Cognitive information processing** (e.g., Rudin-Brown & Noy, 2002; Weller & Schlag, 2004): Here, the basic assumption is that behavioral adaptations are caused by mental representations. These are obtained from information provided by the system or interactions with the system (e.g., the function of the ACC can be extracted from the operating manual; however, it can also be learned by using the system). In case of erroneous or incomplete assumptions about the intended use, behavioral adaptation may result. The build-up and utilization of knowledge can be affected by personality factors (e.g., locus of control) as well as driver expectations (e.g., trust in the system).

The conditions that lead to behavioral adaptation after the introduction of a safety measure are subject of ongoing research. According to Bjørnskau (1995), behavioral adaptations depend on (1) how easy the change to the road system to detect, (2) if road users have already adapted their behavior to the target factor of the safety measure, (3) the size of the positive effect on safety regarding the target factor, (4) if the safety measure reduces the probability of being involved in an accident and (5) if additional utility can be gained from the behavioral adaptation.

Up to now, results of studies evaluating behavioral adaptation to ADAS are of a mixed nature (Dragutinovic, Brookhuis, Hagenzieker & Marchau, 2005). There are studies indicating behavioral adaptations to these systems (e.g., maintaining higher driving speeds or insufficient headways while driving with FCW or ACC, Hoedemaeker & Brookhuis, 1998; Janssen & Nilsson, 1993; Muhrer, Reinprecht & Vollrath, 2012; Rudin-Brown & Parker, 2004; Ward et al., 1995) as well as contrary findings (e.g., fewer or equal occurrences of insufficient headways or lower driving speeds while driving with FCW or ACC; Bao, LeBlanc, Sayer & Flannagan, 2012; Ben-Yaacov, Maltz & Shinar, 2002; Burns, Knabe & Tevell, 2000; Fancher et al., 1998; Janssen & Nilsson, 1993; Stanton, Young & McCaulder, 1997). An important aspect that has sometimes been neglected in previous research is the assessment whether the detected behavioral effects lead to safety-critical consequences (e.g., if a behavioral adaptation in car-following behavior is not only present but has to be classified as safety-critical with regard to common threshold values for the identification of critical following behavior). Another issue that has rarely been addressed is the question if behavioral adaptations also affect the drivers' distribution of attention. For example, Rudin-Brown and Parker (2004) as well as Fancher et al. (1998) showed that driving with ACC leads to an increase in the processing of secondary tasks while driving, indicating an attention shift away from the primary driving task. A similar adverse effect on the distribution of attention following the presentation of FCWs has been reported by Wege, Will and Victor (2013) and Muhrer et al. (2012). In contrast, Sayer, Mefford, Shirkey and Lantz (2005) report that the assistance option provided by ACC and FCW did not cause drivers to engage more frequently in secondary tasks in a naturalistic driving study.

With these findings in mind, a valuation of expected behavioral adaptations must be called for in addition to direct effectiveness verification of newly introduced safety measures. The present study illustrates this based on the example of a predictive system that warns drivers of imminent congestion tails on the road section ahead. The following section will first explain the traffic-related literature that forms the background for the realization of the simulation environment of this study.

1.3 Traffic environment at the transition from flowing traffic to congested traffic

Safely operating a vehicle can be considered a dynamic control task: In order to prevent collisions, drivers observe changes in the traffic environment constantly (Koornstra, 1993; Van der Hulst, Meijman & Rothengatter, 1999) and adapt their driving behavior and attention allocation accordingly (Brown, Lee & McGehee, 2000; Cooper, Vladisavljevic, Medeiros-Ward, Martin & Strayer, 2009; Muhrer & Vollrath, 2010; Schweitzer, Apter, Ben-David, Liebermann & Parush, 1995). For this reason, it can be expected that the occurrence of behavioral adaptations to predictive congestion tail warnings may depend on the respective traffic situation.

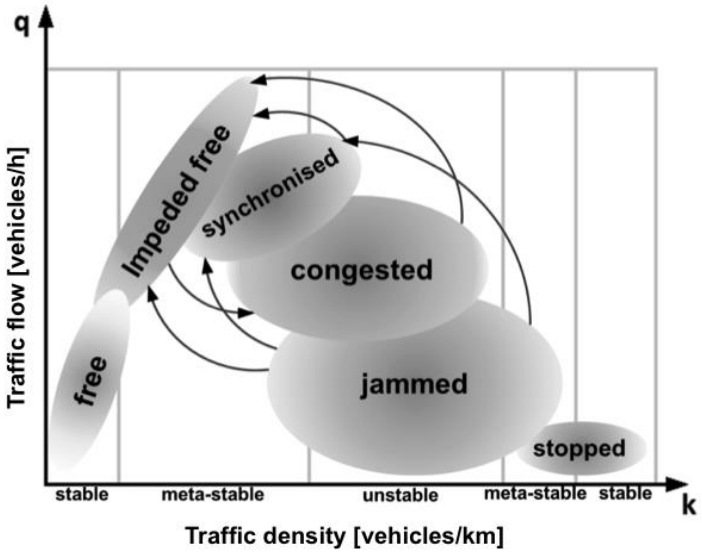

Figure 1: Transition from traffic situations with flowing traffic ('impeded' free flow and synchronized traffic) and congested traffic (according to Kim (2002), Page 21)

In accordance with the so-called 'three-phase traffic theory' (Kerner, 2004; Kerner & Rehborn, 1997), two main types of transitions from flowing traffic to jammed traffic are considered in this study (based on Kim (2002) and Kerner (2004), see Figure 1):

a) Congestion tails with **free flow traffic**: Transition from free flow to jammed traffic with a relatively sudden deceleration in speed when approaching the tail end of a congestion (speed range: 0 to 110 km/h).

b) Congestion tails with **synchronized traffic**: Transition from synchronized to jammed traffic with a relatively smooth deceleration in speed (speed range: approximately 0 to 70 km/h).

Although other kinds of transitions to jammed traffic are possible, transitions from free and synchronized flow to jammed traffic have been described in great detail both theoretically and empirically (e.g., Kerner & Rehborn, 1997; Neubert, Santen, Schadschneider & Schreckenberg, 1999; Knospe, Santen, Schadschneider & Schreckenberg, 2002; Lubashevsky, Mahnke, Wagner & Kalenkov, 2002) which makes it possible to implement them in a driving simulation as an environment for empirical studies. Table 1 summarizes the qualitative parameters for the differentiation of traffic conditions such as 'free flow' and 'synchronized traffic' (from Totzke et al., 2011). Both traffic conditions represent principal test situations for the verification of both the effectiveness of congestion tail warnings (when approaching the end of a congestion) and possible behavioral adaptations (in situations where congestion tails are possible, but do not occur).

Table 1: Differences between 'synchronized' and 'free flow' traffic conditions based on congestion tail situations (from Totzke et al. (2011))

	Traffic condition	
Criterion	**Synchronized traffic**	**Free flow traffic**
Lane speed	Lower than the free flow traffic, however, relatively high speeds are still possible	High values, relatively random speed selection possible
Speed difference between lanes	Speeds on several lanes are comparable	Higher speeds on the fast lane
Lane changes	Frequent lane changes	Less frequent lane changes, vehicles can freely change lanes
Lane capacities	Capacity differences between the lanes are converging	Increased capacity on the slow lane
Vehicle convoys	Greater distances between vehicles; small convoys	Some large convoys traveling at close distances
Characteristic of collapsing speed	At first, minor reduction of speed, followed by a collapse	Abrupt collapse of speed

1.4 Studies on the effectiveness of congestion tail warnings

Numerous studies have been conducted on the effectiveness of congestion tail warnings (e.g., Alm & Nilsson, 2000; Popiv, Rommerskirchen, Bengler, Duschl & Rakic, 2010; Totzke et al., 2011; Totzke, Volk, Naujoks & Krüger, 2013; Van Driel, Hoedemaeker & van Arem, 2007; Werneke, Kleen & Vollrath, 2013). For example, Van Driel et al. (2007) report that driving speeds are reduced more timely if drivers are informed about the remaining distance to a congestion tail by an in-vehicle device compared to non-assisted driving during a simulator study. Similarly, Alm and Nilsson (2000) demonstrate that infrastructure-based warnings, which varied in their amount of detail, lead to an earlier reduction of driving speeds when approaching a congestion tail compared to non-assisted driving. The design of the different warnings (e.g., distance information only vs. additional request to reduce driving speed) had no influence on their effectiveness. Popiv et al. (2010) conducted a driving simulator study comparing display alternatives of an in-vehicle device (birds-eye view vs. iconic display) to forewarn drivers about different potentially critical driving situations in which a brake reaction was necessary, with one of them being a congestion tail. It was found that drivers apply their brakes earlier and with lower brake pressure during assisted driving compared to non-assisted baseline driving. Again, there was no effect with regard to the warning design. In contrast, Totzke et al. (2011) investigate the effects of a warning indicating the 'precise' vs. 'imprecise' position of the congestion tail using a driving simulator and found a positive effect of the precise location warnings as compared to non-assisted driving (e.g., earlier brake readiness and earlier brake onset as well as less forceful braking); whereby imprecise warnings (without distance indication) did not indicate any positive effects on driving behavior. In summary of all studies, the results pertaining to the effectiveness of congestion tail warnings indicate a positive outcome with regard to driving behavior when approaching a congestion tail: The drivers apply the brakes earlier and with less force when approaching the respective congestion tail.

1.5 Research aim

All available studies on congestion tail warnings mainly focus on the direct proof of their effectiveness. The investigation of not-intended behavioral adaptations due to the introduction of congestion tail warnings has been neglected so far. From the cited research findings pertaining to ACC and FCW, it can be expected that the introduction of a predictive warning system, which assists drivers at an early stage of emerging traffic conflicts, may lead to similar negative behavioral adaptations. In general, predictive congestion tail warnings may cause drivers to exhibit a riskier driving style based on an objective or perceived increase in driving safety (e.g., Fuller, 1984; Näätänen & Summala, 1976; Wilde, 1988) or on relying too much on the system's capabilites (e.g., Rudin-Brown & Noy, 2002; Weller & Schlag, 2004).

The present study represents a further assessment of the Totzke et al. (2011) study on the effectiveness of predictive congestion tail warnings that has already shown their potential to increase driving safety while approaching congestion tails. For the investigation of possible (negative) behavioral adaptation effects situations were used in which the tail of a congestion was probable, however, did not occur along the way. In this case, the drivers passed through a situation with or without the display of a potential assistance option, respectively, provided by a predictive congestion tail warning. Changes in driving behavior (i.e., speed, distance behavior, brake readiness) as well as in the involvement in a secondary task, caused by the introduction of the warning system are observed under different traffic conditions (i.e., drivers are nearing the congesting tail with free or synchronized traffic, respectively). Age has been introduced into the study as an exploratory factor. Although some authors have proposed that age-related impairments may be compensated by in-vehicle technologies (Suen, Mitchell & Henderson, 1998; Vrkljan & Miller-Polgar, 2005), these technologies may also lead to additional distraction, cognitive overload or a change in compensatory driving behavior of older drivers (e.g., Davidse, 2007; Simões & Pereira, 2009).

2. Methods

2.1 Experimental design

The present study was part of a research project exploring the potential of predictive congestion tail warnings to enhance active safety via wireless communication (Bogenberger, Dinkel, Totzke, Naujoks & Mühlbacher, 2012). The study consisted of two parts that were conducted within the same experimental session:

1. **System effectiveness**: The drivers performed 16 approaches to a variety of congestion tails ('hard congestion tail' = coming from free flow traffic, or 'soft congestion tail' =

coming from synchronized traffic) with or without the assistance of a visual-auditory warning system, respectively. The warnings differentiated in their precision and timing. The results of this study component are reported by Totzke et al. (2011) and are not part of this paper.

2. **Behavioral adaptation**: Additionally, the participants executed eight more driving segments (each approximately 5 km long), using the same traffic conditions (free flow traffic and synchronized), however, without traffic congestions occurring. The participants were informed by means of an in-vehicle display that along these sections congestion tail warnings may not be possible ('assistance not possible' see Figure 2 left) or may be possible ('assistance possible', see Figure 2 right). These road sections are the focus of this study.

Figure 2: Screenshots of the assistance option displays. Assistance option not available (“No service”; left), assistance option provided (right)

The test track was a two-lane highway, 150 km long (see Figure 3 right) with a recommended speed of 130 km/h. The above-mentioned approaches to different congestion tails and the situations with comparable traffic situations (free flow and synchronized traffic), but without congested traffic, were completed within the same experimental trial. The traffic situations were presented in randomized order in order to control carry-over effects.

Figure 3: Driver's cabin of the driving simulator with view of the screen in the center console (left). Screenshot of a driving situation while approaching the tail end of a congestion (right)

During the drive participants performed a secondary task in the form of a menu input. This consisted of the selection of functions from a hierarchical menu system that included secondary tasks in the areas 'navigation', 'entertainment', 'telephone', and 'onboard computer'.

A screen in the lower center console displays the menu system (see Figure 3 left; Rauch, Totzke & Krüger, 2004, for a detailed description). The menu system was controlled by a joystick that was also fitted in the lower center console. Figure 4 shows an example of the menu task sequence 'Activate engine immobilizer'. The menu task was self-paced, i.e., the participants could decide on themselves to start, interrupt and restart the tasks at any time during the simulator.

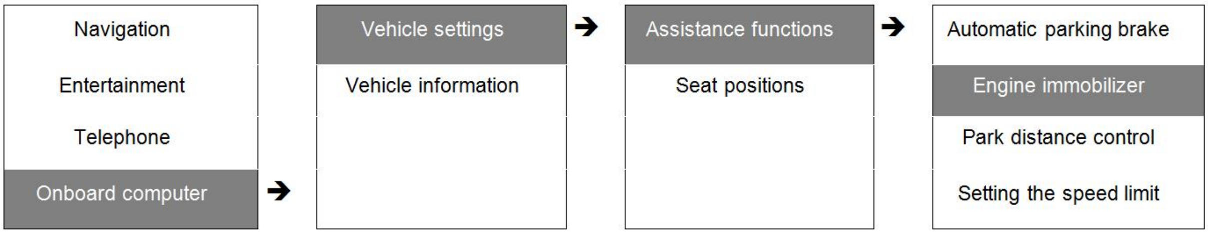

Figure 4: Flowchart of the navigation in the menu system for the task 'Activating engine immobilizer'

2.2 Simulator

The study was conducted in the driving simulator with motion system provided of the Würzburg Institute for Traffic Sciences (WIVW). In order to project the viewing system, three CRT projectors were used that provided a frontal field of vision, similar to a display window of 180°, with LCD displays functioning as exterior and interior mirrors. The motion system of the WIVW driving simulator has 6 degrees of freedom, and can provide lateral accelerations of up to 5 m/s^2 and rotations of up to 100°/s^2. It consists of six electronic and three passive-pneumatic actuators. The vehicle control console is equipped with a full range of instruments, equivalent to a production vehicle (here: BMW 510i). In order to simulate a realistic steering torque, a servomotor based on a steering model was used.

2.3 Test design and independent variables

A 2x2x2 mixed within-between design was selected with the within-subject factors 'traffic condition' ('synchronized traffic' vs 'free flow traffic') and 'assistance option' ('assistance possible’ vs 'assistance not possible') as well as the between-subjects factor 'driver's age' ('younger drivers’ vs. ‘older drivers').

2.4 Dependent variables

It was expected that drivers would neglect their primary driving task if an assistance option was displayed to them and at the same time would exhibit a riskier driving style during car-following if behavioral adaptations were evident. Consequently, various aspects of driver behavior were recorded with a rate of 100Hz during the experimental situations (see Table 2). After each study part (explained in detail in the next paragraph), the participants were asked to rate their own level of fatigue and concentration on a scale ranging from 0 to 15. This was done with the objective to assess if the simulator drives lead to considerable fatigue effects.

The readiness of drivers to respond to other road users was measured by the fraction of time that the drivers put their foot on the brake pedal during the experimental situations via an infrared sensor in the brake pedal. In the case of behavioral adaptations, it was expected that the percent of driving time that the participants are ready to brake would drop. Speed behavior was analyzed by the calculation of the mean and maximum velocity within each of the experimental situations. An increase in mean and maximum velocity was expected in the case of behavioral adaptations. In order to collect the potentially increased attention of the drivers focused towards a secondary task, these activities were also recorded during driving. Here, the sum of the processed tasks per kilometer was taken into account in the analyses. It was expected that the participants would intensify the task processing if assistance was displayed to be possible.

Within the experimental situations surrounding traffic was present that showed the patterns of synchronized or free traffic. The drivers had to trail other vehicles in order to pass the situations. As measures of the quality of longitudinal control, the so-called time headway (THW) and time-to-collision (TTC) were recorded. The THW is defined as the distance to the leading vehicle [in m] divided by the current speed of the ego-vehicle [in m/s] and represents a time-based measure of the distance between two vehicles. In contrast, the TTC is calculated by dividing the current distance to the leading vehicle [in m] by the relative speed between leading vehicle and ego vehicle [in m/s], thus representing the time until the two vehicles would collide if they continued driving with the same speed (Hayward, 1972; van der Horst, 1990; Vogel, 2003). For each of the experimental situations, the minimum THW and minimum TTC were calculated. In the case of behavioral adaptations, it was expected that drivers would pay less attention to longitudinal control and possibly produce lower values of THW and TTC during car-following. Table 2 summarizes the parameters and the anticipated behavior changes in case of (negative) behavioral adaptations.

Table 2: Dependent variables

Variable	Unit	Anticipated changes in the case of behavior adaptations
Self-rating of driver state		
Rated concentration level	[0..15]	-
Rated fatigue level	[0..15]	-
Speed		
Medium velocity Maximum velocity	[kph] [kph]	Increase when assistance is possible
Longitudinal control		
Minimum time headway (THW) Minimum time-to-collision (TTC)	[s] [s]	Decrease when assistance is possible
Distraction and brake readiness		
Processed secondary tasks	[no. of tasks per km]	Increase when assistance is possible
Brake readiness	[% driving time]	Decrease when assistance is possible

In order to further assess the distance parameters time-to-collision (TTC) and time headway (THW), common threshold values for the identification of critical headways were used (TTC_{min}: 1s, Hayward, 1972; THW_{min}: 1s, Fairclough, May & Carter, 1997). The selection of appropriate thresholds to distinguish between safe and unsafe following behavior has been a controversial issue in the past. The aim in applying the above mentioned thresholds was to identify severe traffic conflicts during car-following. The applied TTC threshold of 1s was originally formulated by Hayward (1972) in order to distinguish between so-called ‘near-misses’ and safe driving situations. Van der Horst (1990) and Hydén & Linderholm (1984) proposed a comparable threshold of 1.5s. Higher thresholds have been put forward by other researchers (e.g., Minderhoud & Bovy, 2001: 3s; Hirst & Graham, 1997: 4s; Dijkstra et al., 2010: 2.5s). As van der Horst and Hogema (1993) noted these higher TTC-values (e.g., 4s) may serve as a reasonable basis for identifying potentially dangerous driving situations that may justify activations of FCWs. In contrast, the more conservative approach of the present study was chosen in order to identify truly severe traffic conflicts (in line with so-called ‘near misses’, Hayward, 1972). The THW threshold of 1s was adapted from earlier studies (De Waard & Brookhuis, 1997; Evans & Wasielewski, 1983; Fairclough et al., 1997; Groeger, Chapman & Stove, 1994). Other thresholds have been proposed with regard to THW as well (e.g., Michael, Leeming & Dwyer, 2000: 2s; Rudin-Brown & Parker, 2004: 2s). As the 1s-threshold corresponds to values justifying fines for close following in several countries (e.g., Germany: 0.9s, Sweden, 1.0, see Vogel, 2003) and has commonly been used it was selected in this study.

A repeated measures univariate Analysis of Variance (ANOVA) was used to assess differences between the experimental conditions, with the within-factors 'traffic condition' and 'assistance option' and the 'age of driver' as between-factor on an α-level of 5%.

2.5 Procedure

The test session was structured in four main parts:

1. Instruction (duration up to approx. 40 min): Instruction and demonstration of the menu task that should be processed during the vehicle operation. Subsequently, the task was practiced. A total of 45 tasks were processed in order to minimize learning effects during the main part of the study.
2. Practice drive (duration approx. 15 min): Short drive in order to re-familiarize the drivers with the driving simulation as well as exercising the processing of the menu task while driving (the term ‘re-familiarize’ is used because all participants had already taken part in a simulator training prior to the study). Furthermore, the congestion tail warning was experienced during a noncritical situation, and a written brief instruction was given to explain the warning system. At the start of the practice drive participants were asked to give a self-rating on their level of fatigue and concentration.
3. Test drives (duration approx. 90 min): Two drives lasting 45 minutes each, during which the tail end of a congestion was approached eight times. The individual approaches of the congestion differentiated by applying the above-mentioned variations (traffic condition, warning precision and warning timing). Furthermore, four road sections (one half with synchronized traffic, the other half with free flow traffic) were passed through with or without display of the assistance option (assistance possible vs. not possible), respectively. The test drive was split into two parts in order to provide the participants a rest period and to counteract fatigue effects. At the beginning and after each of the two drives, the participants were asked to give a self-rating on their level of fatigue and concentration.
4. Subsequent interview and debriefing (duration approx. 30 min)

2.6 Instruction

Participants were instructed verbally to complete the test course in a timely manner without violating the traffic code (maintaining safe headway, complying with the driving in the right lane regulation, no passing on the right lane, etc.). The participants were asked to perform the secondary task only when they evaluated the traffic situation as to be safe enough. It was emphasized that driving safety was always of greatest importance, and that the participants could interrupt working on the secondary task at any point if they judged the driving situation not to be safe enough to perform the secondary task.

2.7 Sample

A total of N = 16 participants between the ages of 25 to 39 years (N = 8, 'younger drivers') or 57 to 72 years (N = 8, 'older drivers') took part in this study. At the time of the test, the younger participants had between 4 to 15 years of driving experience (M = 9.4, SD = 3.2), while the older participants had between 37 and 50 years of experience (*M* = 42.5, *SD* = 4.3). In the preceding year, the younger participants had driven an average of 8,813 km (*SD* = 4,488 km), while the older participants had travelled approximately 12,250 km (*SD* = 3,694 km). The participants were selected from an existing WIVW test driver panel and received extensive simulator training prior to the start of the study. The standardized training (Hoffmann & Buld, 2006) was aimed at making participants familiar with the handling of the simulated vehicle (e.g., accelerating, negotiating curves, executing turning maneuvers, braking) and reducing simulator sickness.

The experimental session took approx. 3.5 hours. The participants received an expense allowance for taking part in the test.

3. Results

As can be seen in Figure 5 the self-ratings of fatigue and level of concentration vary within the experimental session (fatigue: $F_{4.12} = 3.29$, $p = .049$, $\eta^2 = .52$; concentration: $F_{4.12} = 3.08$, $p = .058$, $\eta^2 = .51$).

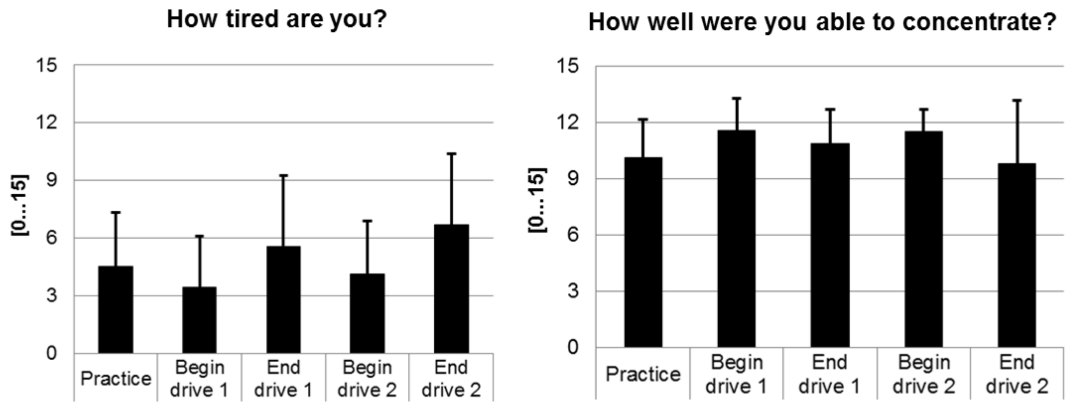

Figure 5: Self-rating of fatigue (left) and level of concentration (right) displayed as mean value and standard deviation

Planned comparisons with the initial ratings at the beginning of the practice trial show that participants only rate themselves as being more tired at the end of the last test drive (see Table 3). Furthermore, no negative time effect on the participants' self-reported level of concentration is found, but rather an increase at the beginning of the two test drives (see Table 3).

Table 3: Planned contrasts (comparison with practice drive) derived from ratings of fatigue and concentration

Difference	Fatigue rating				Concentration rating			
	t	df	p	d	t	df	p	d
Practice vs. Begin drive 1	2.08	15	.056	0.52	**-2.93**	**15**	**.010**	**-0.73**
Practice vs. End drive 1	-1.41	15	.180	-0.35	-1.46	15	.164	-0.37
Practice vs. Begin drive 2	0.58	15	.573	0.14	**-3.30**	**15**	**.005**	**-0.82**
Practice vs. End drive 2	**-2.78**	**15**	**.014**	**-0.70**	0.41	15	.690	0.10

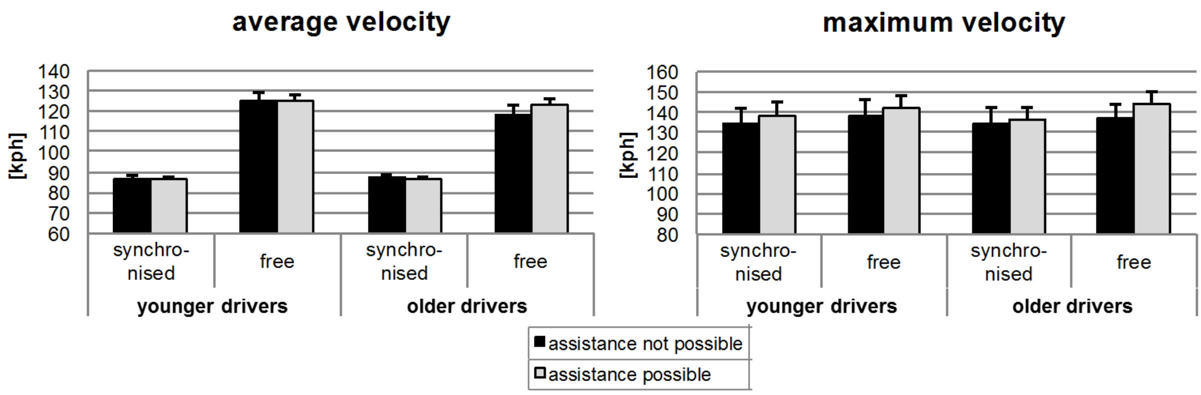

Figure 6: Average speed (left) and maximum speed (right) displayed as mean value and standard deviation

With regard to the average velocity, an effect of the assistance option cannot be seen: The participants select comparable velocities, whether or not assistance is displayed to be possible (main effect: assistance option, see Figure 6 left, or Table 4). As expected, the participants adjust their velocity according to the surrounding traffic: The participants travelled at a speed of approx. 120 km/h in free-flow traffic and approx. 85 km/h in synchronized traffic (main effect: traffic condition). Furthermore, in free flow traffic older drivers tend to drive slower than younger drivers; however, this does not apply in synchronized traffic (interaction: traffic condition x age group).

Table 4: ANOVA results derived from the average speed and maximum speed variables

Effect	$Velocity_{mean}$				$Velocity_{max}$			
	F	df	p	η^2	F	df	p	η^2
Assistance option	2.27	1, 14	.155	0.14	14.43	1, 14	**.002**	0.51
Assistance option x age group	1.47	1, 14	.246	0.10	0.05	1, 14	.830	0.00
Traffic condition	1334.00	1, 14	**.000**	0.99	29.99	1, 14	**.000**	0.68
Traffic condition x age group	5.83	1, 14	**.030**	0.29	1.02	1, 14	.329	0.07
Assistance option x traffic condition	4.47	1, 14	.053	0.24	0.35	1, 14	.265	0.09
Assistance option x traffic condition x age group	2.82	1, 14	.115	0.17	3.58	1, 14	.079	0.20
Age group	2.67	1, 14	.125	0.16	0.01	1, 14	.918	0.00

Regardless of the driver's age and the surrounding traffic, the participants increase their maximum speed if an assistance option is displayed (main effect: assistance option, see

Figure 6 right, or Table 4). In free flow traffic older as well as younger drivers - analogous to the effects for average speeds - use higher maximum speeds than in conditions with synchronized traffic (main effect: traffic condition). However, no age effect on using maximum speeds is found (main effect: age group).

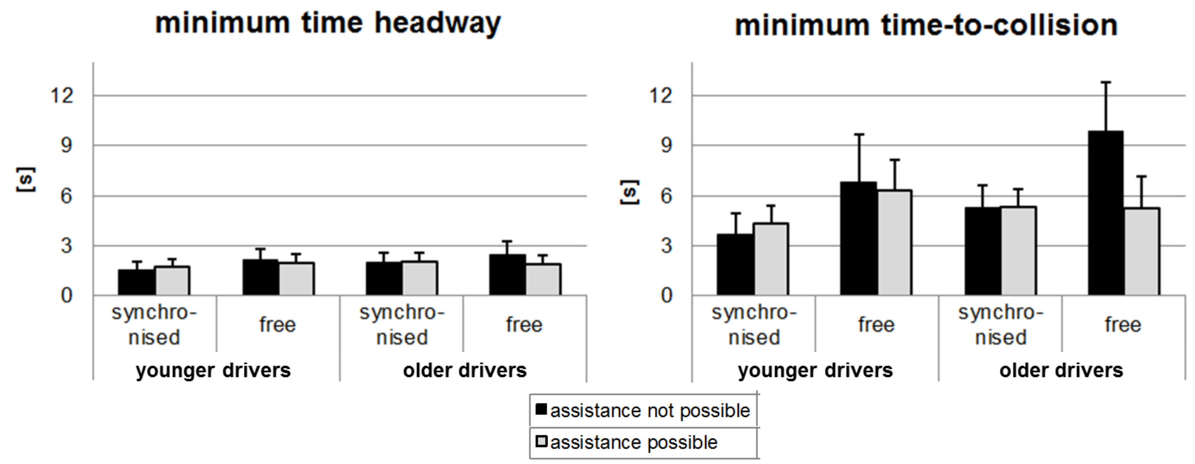

Figure 7: Minimum time headway (left) and minimum time-to-collision when following another vehicle (right). Here, mean values and standard deviations are illustrated

The display of the assistance does not influence the minimum time headways (THW_{min}) while following other vehicles (main effect: assistance option, see Figure 7 left or Table 5). The minimum time headways are also not different in the investigated traffic conditions or in the age groups (main effect: traffic condition and age group, see Table 5). On average, the minimum time headways are clearly above a critical value of 1 sec.

Table 5: ANOVA results derived from the THW_{min} and TTC_{min} variables

Effect	THW_{min}				TTC_{min}			
	F	df	p	η^2	F	df	p	η^2
Assistance option	1.38	1, 13	.261	0.10	3.98	1, 13	.067	0.24
Assistance option x age group	1.55	1, 13	.236	0.11	4.56	1, 13	.052	0.26
Traffic condition	1.65	1, 13	.222	0.11	13.93	1.13	**.003**	0.52
Traffic condition x age group	0.36	1, 13	.559	0.03	0.06	1, 13	.819	0.00
Assistance option x traffic condition	3.71	1, 13	.076	0.22	7.20	1, 13	**.019**	0.36
Assistance option x traffic condition x age group	0.37	1, 13	.552	0.03	2.58	1, 13	.132	0.17
Age group	1.38	1, 13	.261	0.10	3.98	1, 13	.067	0.24

The minimum values of the time-to-collision (TTC_{min}) are shown in Figure 7 right (ANOVA results: see Table 5). Based on the display of assistant options, TTC_{min} values are lowered in a traffic environment with free flow but not with synchronized traffic (interaction: assistance option x traffic condition). Regardless of the driver's age, lower TTC_{min} values can be seen in synchronized traffic compared to free flow traffic (main effect: traffic condition). As indicated by Figure 7 right, these effects seem to originate mainly from older drivers producing lower TTC_{min} values in free flow traffic if an assistance option is displayed to them. However, the three-way interaction (interaction: assistance option x traffic condition x age group) needed to statistically support this result is non-significant, although a tendency of older drivers rather than younger drivers to produce lower TTC_{min}-values if an assistance option is displayed is evident (interaction: assistance option x age group). In spite of the decrease in TTC_{min} values, it must be noted that - on average - these values still exceed the 1s-threshold that is considered as critical.

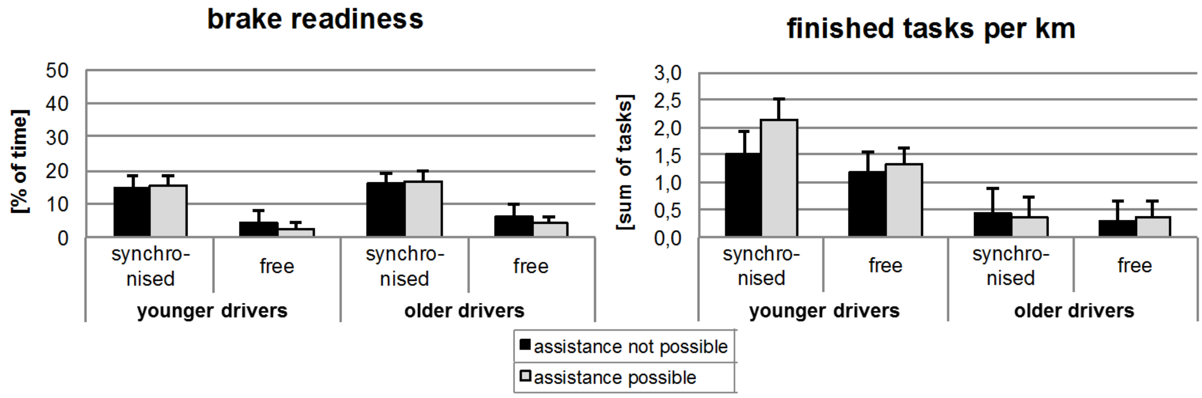

Figure 8: Break readiness in percent of the driving time (left) and processed tasks per kilometer (right) are displayed as mean value and standard deviation

As indicated in Figure 8 left or Table 6, the traffic condition impacts the relative frequency of the brake readiness. The drivers keep their foot above the brake pedal for a higher percentage of driving time when driving in synchronized traffic than in free flow traffic (main effect: traffic condition). Effects of the drivers' age and the display of the assistance option are not evident (main effect: age and assistance option).

Table 6: ANOVA results derived from brake readiness and task processing variables

Effect	Brake readiness				Task processing			
	F	df	p	η^2	F	df	p	η^2
Assistance option	0.98	1, 14	.339	0.07	4.76	1, 14	**.047**	0.25
Assistance option x age group	0.06	1, 14	.805	0.01	5.43	1, 14	**.035**	0.28
Traffic condition	127.07	1, 14	**.000**	0.90	13.27	1, 14	**.003**	0.49
Traffic condition x age group	0.16	1, 14	.698	0.01	7.71	1, 14	**.015**	0.36
Assistance option x traffic condition	1.63	1, 14	.222	0.10	1.30	1, 14	.273	0.09
Assistance option x traffic condition x age group	0.00	1, 14	.951	0.00	4.35	1, 14	.056	0.24
Age group	1.09	1, 14	.314	0.72	36.28	1, 14	**.000**	0.72

Due to the display of the assistance option, younger drivers are more likely to turn to secondary activities than the older participants in both traffic conditions. That is to say they process more tasks per driven kilometer if an assistance option is displayed (interaction: assistance option x age group, see Figure 8 right or Table 6; due to the hybrid interaction, the main effect 'assistance option' cannot be interpreted). This effect seems to originate mainly from younger drivers performing more secondary tasks if an assistance option is possible in synchronized traffic (marginally significant interaction assistance option x traffic condition x age group). While older drivers hardly engage in the secondary task in both traffic conditions, younger drivers generally complete more tasks than the older drivers (main effect: age group). Furthermore, younger drivers, but not older drivers perform more activities in traffic environments with synchronized traffic than in traffic conditions with free flow (interaction: age group x traffic condition; due to the hybrid interaction, the main effect 'traffic condition' cannot be interpreted).

4. Summary and discussion

The focus of this study was the investigation of so-called '(negative) behavioral adaptation' effects when using predictive warning systems, such as congestion tail warnings. These warning systems should alert drivers at an early stage of a conflict situation by using wireless communication technologies. The design aspects of such systems as well as their potential to enhance traffic safety have been described in a previous paper of the authors (Totzke et al., 2011). In order to investigate the effects of behavioral adaptation, situations were introduced in which the participants perceived the occurrence of congestion tails as probable, because they had previously encountered and had been warned about congestion tails in similar traffic situations. However, congestions did not occur in these road segments. The situations were completed in two different conditions of the surrounding traffic ('synchronized traffic' and 'free flow traffic') as well as with and without the display of a potential assistance option that was provided by the congestion tail warning, respectively. The impact of displaying an assistance option was observed on various aspects of driving behavior (e.g., following behavior and speed regulation). According to established theories of behavioral adaptation it was expected that the drivers would show a riskier driving style if an assistance option was displayed.

Due to the display of assistance options, behavioral adaptation effects became clear. Table 7 summarizes those: When compared to driving without an assistance option drivers increased their maximum speed. Additionally, lower TTC_{min} values could be found in free flow traffic. This finding applied to older drivers in particular: During non-assisted driving older drivers' TTC_{min} values were considerably higher when driving in free flow traffic than those of younger drivers, but not if an assistance option was displayed. This difference between age groups with regard to non-assisted driving can be interpreted as compensatory behavior of older participants. Displaying an assistance option to older drivers seemingly diminished their compensatory behavior and led to a decrease of TTC_{min} values. Furthermore, younger drivers - but not older participants - showed an intensified processing of a secondary task. This holds especially true for driving in synchronized traffic, possibly due to lower driving speeds compared to free flow traffic, as driving speed is related to feelings of risk and of mental effort (Lewis-Evans, De Waard & Brookhuis, 2011).

Table 7: Results summary: Behavioral adaptation while driving with a congestion tail warning

Variables	Change caused by the display of the assistance option
Medium speed	No change
Maximum speed	Increase of the maximum speed (main effect: $F_{1,14}$ = 14.43, p = .002) by a maximum of approx. 7 km/h.
Brake readiness	No change
Minimum time headway	No change
Minimum time-to-collision	Fewer minimum TTC during free flow of traffic (significant interaction: F1,14 = 7.20, p = .019). The difference is approx. 4.5 sec; however, the TTCmin values are still exceeding a value of 1s (Hayward, 1972) that is considered as critical. The reduction in minimum TTC values applies in particular to older participants (marginally significant interaction $F_{1,14}$ =4.56, p = .052).
Task processing per kilometer	Younger drivers complete approx. 40% more secondary tasks (significant interaction: $F_{1,14}$ = 5.43, p = .035). The increase in task processing among younger drivers is particularly pronounced during synchronized traffic (marginally significant interaction: $F_{1,14}$ = 4.35, p = .056). For older drivers, the processing of secondary tasks does not change.

While the results with respect to speed and maintaining headway can be assessed as non-critical since they did not drop below critical safety thresholds (Hayward, 1972; Fairclough et al., 1997), the increased secondary task involvement of younger drivers must be seen as potentially critical. The increase in task processing did not lead to compensatory behavior, as would be expected from other studies dealing with driver distraction (e.g., lowering speed (Horberry, Anderson, Regan, Triggs & Brown, 2006; Rakauskas, Gugerty & Ward, 2004) or increasing following distance (Jamson, Westerman, Hockey & Carsten, 2004; Strayer & Drew, 2004)). However, it must be assumed that the actual effect on attention-requiring behavior depends on the type of the secondary task, specifically on how long the task requires the drivers to take their eyes off the road (NHTSA, 2012). The task used in this study was a rather simple visual-manual task that was self-paced and could be interrupted at any time (see Young, Regan & Lee, 2009 for a discussion on this topic). Moreover, the effect of increased secondary task processing may be influenced by the instructions given in the study. The participants were explicitly requested to work on the secondary task as long as traffic safety was not affected negatively.

With regard to the study design, some methodological issues have to be discussed, as the observed behavioral adaptation effects may be partly due to the within-subject design. It is possible that drivers changed their behavior either due to learning effects or due to fatigue caused by the rather long experimental sessions. Care was taken to control these carry-over effects with regard to the test procedure: Firstly, the experimental situations were completed in randomized order. Secondly, the participants were familiar with both handling of the simulated vehicle (by a driver training prior to the study and a warming-up phase at the beginning of the study) and the secondary task (by a practice period prior to the test drives) so learning effects were minimized. As all participants passed the situations with and without congestion tails within the same experimental session, it seems unlikely that they learned to identify those situations in which they would not encounter congestion tails. Thirdly, the experimental session was split into two drives to allow the participants a rest period in order to reduce fatigue effects. Self-ratings of the participants suggest that the subjective level of fatigue only increased in the very last part of the study. Importantly, drivers did not report an accordingly lowered concentration level.

Further research is needed in particular with regard to translating the results into everyday driving behavior. Particularly, the relatively short test times spend in the simulated environment and the used secondary tasks require further attention. The actual size of behavioral adaptation effects in everyday driving behavior (i.e., change of speed, following distance and focus of attention) can only be determined in real life scenarios (e.g., so-called 'Field Operational Tests') with realistic secondary activities (i.e., distraction sources inside the vehicle that are actually performed while driving). Also, research pertaining to behavioral adaptations due to higher levels of vehicle automation is an important issue that has to be addressed in future research (Gouy, Diels, Reed, Stevens & Burnett, 2012). Further studies in the future will give insight into these questions.

4. Conclusion

In conclusion, the results suggest that (negative) behavioral adaptations must be anticipated due to the introduction of predictive warning systems. Earlier studies have shown this in simulator and field trials of Forward Collision Warning (FCW) and Adaptive Cruise Control (ACC). During effectiveness tests of predictive warning systems, in particular congestion tail warnings, such effects of negative behavioral adaptations have not been assessed yet. Based on the results at hand, it is recommended to consider these effects in future studies of predictive warning systems.

5. Acknowledgment

This study is based on the research sponsored by the German Federal Highway Research Institute (BASt) within the project 'Konzept zur Ermittlung der Sicherheitswirkungen von digitalen Verkehrsinformationen' (Bogenberger et al., 2012; FE 82.0371/2009).

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