This document is a postprint version of the following article:

Title: Timing of early warning stages in a multi stage collision warning system: Drivers' evaluation depending on situational influences

By: Winkler, Susann; Werneke, Julia; Vollrath, Mark

Published in: Transportation Research Part F: Traffic Psychology and Behaviour - Volume 66, January 2016, Pages 57-68

Publisher: Elsevier | Year: 2016

DOI: 10.1016/j.trf.2015.11.001

Brought to you by the Scientific
Information Service for Mobility
and Transport Research

Fachinformationsdienst Mobilitäts- und Verkehrsforschung

Website: www.fid-move.de

Repository: publish.fid-move.de

Contact: publish@fid-move.de

© 2019. This manuscript version is made available under the CC-BY-NC-ND 4.0 license.

<http://creativecommons.org/licenses/by-nc-nd/4.0/>

Timing of early warning stages in a multi-stage collision warning system: Drivers' evaluation depending on situational influences

Susann Winkler^{a,*}, Julia Werneke^b and Mark Vollrath^a

Transportation Research Part F: Traffic Psychology and Behaviour

^a Susann Winkler, Technische Universität Braunschweig, Department of Traffic and Engineering Psychology, Gaußstraße 23, 38106 Braunschweig, Germany, Phone: +49 (0) 531 391 3654, Fax: +49 (0) 531 391 8181, E-mail address: susann.winkler@tu-braunschweig.de

^b Julia Werneke, Chalmers University of Technology, Department of Applied Mechanics, Division of Vehicle Safety, Accident Prevention Group, Lindholmspiren 3, 41296 Gothenburg, Sweden, Mobile: +46 (0) 76 768 2442, Email: julia.werneke@chalmers.se

^a Mark Vollrath, Technische Universität Braunschweig, Department of Traffic and Engineering Psychology, Gaußstraße 23, 38106 Braunschweig, Germany, Phone: +49 (0) 531 391 3644, Mobile: +49 (0) 151 5471 1638, Fax: +49 (0) 531 391 8181, E-Mail: mark.vollrath@tu-braunschweig.de

*Corresponding Author: Susann Winkler, TU Braunschweig, Department of Traffic and Engineering Psychology, Gaußstraße 23, 38106 Braunschweig, Germany, Phone: +49 (0) 531 391 3654, Fax: +49 (0) 531 391 8181, E-mail address: susann.winkler@tu-braunschweig.de

Abstract

By means of car2x communication technologies (car2x), driver warnings can be presented to drivers quite early. However, due to their early timing, they could be misunderstood by drivers, distract or even disturb them. These problems arise if, at the moment of the warning, the safety-critical situation is not yet perceivable or critical. In order to examine, when drivers want to receive early warnings as a function of the situation criticality, a driving simulator study was conducted using the two early warning stages of a multi-stage collision warning system (first stage: *informing the driver*; second stage: *prewarning the driver*). The optimum timing to activate these two early warning stages was derived by examining the drivers' evaluation of these timings concerning their appropriateness and usefulness. As situational variation, drivers traveling at about 100 km/h were confronted with slow-moving traffic either driving at 25 km/h or 50 km/h at the end of a rural road.

In total, 24 participants were tested in a within-subjects design (12 female, 12 male; $M = 26.6$ years, $SD = 7.2$ years). For both stages, drivers preferred an earlier timing when approaching slow moving traffic traveling at 25 km/h (first stage: 447 m, second stage: 249 m ahead of the lead vehicle) compared to 50 km/h (first stage: 338 m, second stage: 186 m ahead of the lead vehicle). The drivers' usefulness rating also varied with the timing, spanning a range of 8 s for driver-accepted timing variations and showed correspondence to the drivers' appropriateness ratings. Based on these results and those of a previous study, a timing function for each of the two early warning stages depending on the speed difference between the safety-critical object and the host vehicle is presented. Indirectly, similar adaptations are already implemented in current collision warning systems, which use the time-to-collision to give drivers acute warnings in a later stage, when an immediate reaction of the driver may still prevent a collision. However, this study showed that drivers also favor this kind of adaptation for earlier warning stages (*information* and *prewarning*). Thus, adapting the timing according to the drivers' preferences will contribute to a better acceptance of these collision warning systems.

Highlights

- Evaluating how to time two early warning stages of a multi-stage collision warning
- Drivers rating appropriateness and usefulness of timings to find optimum
- Optimum timing depends on situation influence (speed difference to critical object)
- Drivers' usefulness rating varies with timings leading to acceptable time ranges
- Estimating optimum activations of early warning stages by speed difference

Keywords: car2x communication; early warning stages' timing, multi-stage collision warning system; critical object dynamics; driving simulator study, drivers' evaluation

1.1 Introduction

In the last years, driver collision warnings based on car2x (wireless cooperative data exchange between a host vehicle and the infrastructure or other nearby vehicles, see Tan & Huang, 2006) have become increasingly important. They can warn drivers in very early stages when the hazard is too far away to be recognized by the drivers and the situation is not yet critical or dangerous (Naujoks & Totzke, 2014). Thus they provide drivers with more time and distance to become aware of the upcoming situation, evaluate its criticality and render them ready to respond accordingly with the most appropriate action (Posner, Klein, Summers & Buggie, 1973; Naujoks & Neukum, 2014; Zarife, 2014). First studies have already shown that drivers adapt their driving behavior to oncoming critical situations (e.g., by reducing their speed) when being warned in advance (Abe & Richardson, 2006; Lenné, Triggs, Mulvihill, Regan, & Corben, 2008; Popiv, Rommerskirchen, Bengler, Duschl, & Rakic, 2010; Tang & Yip, 2010; Totzke, Naujoks, & Mühlbacher, 2011; van Driel, Hoedemaeker, & van Arem, 2007; Weiß, 2011; Werneke, Wäller, Gonter, Rhede, & Vollrath, 2011). This, in turn, enables drivers to react much milder and more stress-free when finally approaching the critical situation, which eventually leads to a safety benefit (Jones & Hansman, 2007). For example, Lee, McGehee, Brown, & Reyes (2002) discovered a reduction of the number of collisions by 80.7% and of the collision severity by 96.5% (assuming collision severity is proportional to kinetic energy) when using an early collision warning compared to no warning, whilst a late warning had less benefit (reduction of collisions by 50.0% and of severity by 87.5%).

Consequently, driver warnings can have a big impact on road safety, with an additional benefit through their timing (McGehee, Brown, Lee, & Wilson, 2002). Early warnings seem to be more promising than late ones, but this should not be generalized to the idea of always warning “As Early As Possible” (Reichart, 1993). The earlier the timings of driver warnings, the higher the probability of false alarms as the safety-critical situation might have mitigated itself by the time of arrival or actually turn out to be neutral (Jones & Hansman, 2007; Schmidt, 2012). Even if given correctly, the early warning presentation might still lead to driver distraction or annoyance (e.g., Brown, Lee, & McGehee, 2001; Geiser & Nirschl, 1993; Seiler, Song, & Hedrick, 1998), especially when designed as intrusive as a late warning (Campbell, Richard, Brown, & McCallum, 2007). At worst, drivers might interpret the early warning as being a false alarm (Janssen & Nilsson, 1993; Parasuraman, Hancock, & Olofinboba, 1997) so that a warning presented too early may eventually be ignored (e.g., Horowitz & Dingus, 1992; Lee & Kantowitz, 1998). Additionally, drivers may have forgotten the information by the time it actually becomes relevant. Consequently, there is a trade-off

between giving drivers a time benefit and the risk of reduced subjective usefulness for the drivers (Brown, Lee, & McGehee, 2001).

Due to their moderating effect, the design and especially the timing of such early warnings are of great importance for the acceptance of the entire warning system by the drivers (Zarife, 2014). Hence, it is essential to actually ask the drivers about their needs and to adapt the design of the warning concept accordingly, since highly accepted warning systems are also likely to be used more often (Jamson, Lai, & Carsten, 2008; Ervin, 2005) and thus can spread their benefit better. This study includes the drivers' perspective very early into the process of designing driver warnings by placing great emphasis on the drivers' preferences concerning the timing of such early warnings in terms of subjective appropriateness and usefulness.

A good way to counteract the described contradiction between safety gain and greater risk of annoyance through advanced warning timings, and rather maximize the subjective usefulness of the warning system, could be the use of a multi-stage warning strategy (e.g., General Motors Corporation & Delphi-Delco Electronic Systems, 2002; Jones & Hansman, 2007; Lerner, Dekker, Steinberg, & Huey, 1996; Petermann-Stock & Rhede, 2013; Spence & Ho, 2008; Zarife, 2014). Compared to a single warning stage of imminent danger level (asking for an immediate driver response, see Lenné & Triggs, 2009), a multi-stage concept extends the warning range to more advanced cautionary levels of prewarning or simply informing drivers about a safety-critical situation ahead (asking for an elaborated driver response or mere driver attention, see Posner et al., 1973; Naujoks & Neukum, 2014). Thereby, a multi-stage warning can induce different driver reactions depending on the urgency level and the situation's intervention need with adapted intrusiveness. The early warning stages should be less intrusive as they might be triggered more frequently and would otherwise increase the probability of annoying drivers, whereas later warning stages certainly need a stronger salience to certainly elicit a driver reaction in an emergency (General Motors Corporation & Delphi-Delco Electronic Systems, 2002).

Therefore, the present study uses an already evaluated multi-stage collision warning concept, more precisely it follows the idea of Rhede, Wäller, and Oel (2011, see also Werneke, Kleen, & Vollrath, 2014). They suggest to initially inform drivers very early about an oncoming critical situation in a first stage (*information*) in order to increase their attention and shift awareness towards the situation without demanding an immediate action like braking, but rendering them ready to do so (e.g., Naujoks & Neukum, 2014; Neukum, 2011). However, some drivers may slightly release the accelerator pedal in order to react better when the situation becomes more critical (see, e.g., Werneke et al., 2011). In the second stage (*prewarning*) a more urgent, but still early warning is presented with the aim of reducing speed, mainly by releasing the accelerator pedal and next perhaps also by braking

moderately (e.g., Petermann-Stock & Rhede, 2013). As drivers have already been informed ahead and are thus driving more attentively, this brake reaction does not have to be very strong and drivers can handle the situation without it even becoming critical. Therefore, an acute emergency brake, characteristic for late warning stages (like an *acute warning*; see also Winkler, Kazazi, & Vollrath, 2016) might not be necessary. For a further theoretical background see Zarife (2014), who gives a good overview of an integrated warning process from sending, designing and receiving a warning by combining various relevant models from Shannon and Weaver (1976), Wogalter (2006), Rogers, Lamson, and Rousseau (2000) and Schmidt (2012).

As the timing of the early warning stages seems to have a big impact on the usefulness of a warning system, the question arises *when* to actually trigger these early warning stages. Furthermore, there might be situational influences on the drivers' preferred timing. Previous studies, investigating the optimum timing of driver warnings, also considered situational influences, these ranging from environmental circumstances like road conditions (Raksincharoensak & Nagai, 2008; Seiler et al., 1998, Tang & Yip, 2010) or obstacle type (Hiraoka, Nakata, Tanaka, & Kumamoto, 2008) to driver-related factors like risk perception (Bella & Russo, 2011), age and attention (Tang & Yip, 2010). However, all these studies investigated mainly the influence of situational factors on late warnings. They propose an earlier presentation of the late warnings for more critical situations (like larger speed differences or shorter time-to-collision values to obstacles). Nevertheless, it is still unclear whether those results are applicable to early warning stages since the required driver reactions between these warnings differ respectively as described above. This study intends to provide further insight into that.

A driving simulator study by Werneke et al. (2014) demonstrated that the optimum timing for two early warning stages when approaching a traffic jam (static object) depends on the speed of the host vehicle. With higher speeds, drivers favored warnings at larger distances in order to be able to react adequately. When transforming the distance into time-to-collision (TTC, time to reach the traffic jam when continuing with the same speed), the values were nearly identical for all three conditions examined (urban road, rural road and highway; first stage: 26 s; second stage: 12 s). In the present study, this is adapted to a situation with an upcoming congestion of slow-moving traffic (dynamic object) with varied speed (situation criticality) in order to examine further situational influences on the timing of such early warning stages.

To summarize, the aim of this study was to investigate the optimum timing of two early warning stages of a collision warning system and their usefulness, under the influence of varying situation criticality (necessary reaction times when braking), adjusted by the drivers themselves in order to promote the acceptance of the proposed warning concept. Therefore,

a driving simulator study according to Werneke et al. (2014) was conducted, in which drivers were asked to actively select their optimum timing of the information (first stage) and the prewarning signal (second stage) amongst a set of presented timings, depending on the speed of the slow moving traffic they were approaching (dynamic lead vehicle traveling at 25 km/h or 50 km/h). Due to the situational factor, different amounts of deceleration were required from the host vehicle, which was constantly driving at a speed of 100 km/h before the early warning stages were activated. In order to avoid a collision with the slow lead vehicle traveling at 25 km/h, a higher speed reduction was required than for the faster one (50 km/h). According to this, the lead vehicle driving at 25 km/h should lead to earlier preferred timings, since it would take a higher amount of deceleration to adjust the speed in time. However, the effect for the first stage is less clear as it did not yet require an immediate driver reaction.

Furthermore, a subject-based evaluation of the usefulness of all the presented timings was undertaken, in order to make sure that drivers actually considered the timing of the early warning stages as necessary rather than annoying, which has to be regarded particularly when analyzing such early warning stages. In return a high usefulness, as rated by the drivers, also increases the probability of the system reaching greater driver acceptance, which this study pursued as well. As the second early warning stage, triggered subsequently when the safety-critical situation is in greater vicinity, requires a greater physical response (slowing down) in contrast to the first stage, which rather requires an adaptation of attention, a more distinct usefulness curve was expected for the timings of the second stage. Additionally, it was presumed that the timing adaption, due to being relevant for the drivers' usefulness ratings, would result in acceptable time ranges and that the drivers' optimum timing would correspond to the timing with the drivers' highest usefulness ratings.

Moreover, a comparison with the results from Werneke and colleagues (2014) was pursued, in order to analyze whether the speed difference (e.g., between host and lead vehicle) can be used as a combined situational factor to find one general function of the optimum timings or distances to activate such early warnings for both static and dynamic safety-critical objects.

1.2 Method

1.2.1 Multi-stage collision warning concept

The aim of the used multi-stage collision warning concept mentioned above (Rhede et al., 2011, see also Werneke et al., 2014) is to inform drivers well in advance about the potential danger (e.g., traffic jam) so that an imminent collision may be avoided due to already attentive and carefully approaching drivers. As human-machine interface (HMI) the collision

radar of Rhede et al. (2011) from Figure 1 was presented on the dashboard with three segmented rings surrounding an image of the host vehicle (see normal status in Figure 1). While approaching a safety-critical situation (slow-moving traffic), drivers were informed by a first early warning stage (*information*). The aim of this first stage (*“Informing the driver”*) is to give drivers some preparation time when approaching a critical situation, therefore raising and allocating their attention towards the potential danger, making them ready to respond (e.g., Naujoks & Neukum, 2014). A brake reaction by drivers is not yet required. To mark the first stage, a warning triangle for slow-moving traffic accompanied by text (*“Attention slow moving traffic!”*) is presented for 2 s on the dashboard, as can be seen in Figure 1. Subsequently, the outer segment of the collision radar starts to blink in the direction of danger (e.g., in the front) until the second stage starts.

	Normal	First stage: <i>Information</i>		Second stage: <i>Prewarning</i>	
Visual
Auditive
				1kHz („Beep“)	

Figure 1 Modified from Werneke et al. (2014, p. 3), example of the multi-stage collision warning system HMI by Rhede et al. (2011) presented on the dashboard display. The figure shows the two early warning stages plus the status display: normal driving, first stage: *information*, and second stage: *prewarning*. The two displays for the first and second stage, are presented in succession (Werneke et al., 2014).

In the second stage (*prewarning*), the 2 s presentation of the warning triangle with text (*“Slow moving traffic ahead!”*) is supported by a short acoustic warning signal (*“Beep”*). Following this, two of the outer ring segments are activated. The aim of this second early warning stage (*“Prewarning the driver”*) is that the drivers start to decelerate and perhaps also brake gradually, however considerably more moderately than in case of an emergency brake, typical for later warning stages (like an *acute warning*) disregarded in this study.

1.2.2 Driving simulation

This warning concept was examined in the static medium fidelity driving simulator of the Technische Universität Braunschweig. The driving simulator, operating with automatic transmission, consists of a typical car seat, a steering wheel with force feedback, an accelerator and a brake pedal. The virtual scenery, as created by the driving simulation software SILAB (from WIVW; Krüger, Grein, Kaussner, & Mark, 2005; see www.wivw.de),

was projected on three silver screens (left, ahead, right) for the scenery, while two LCD screens with 1400x1050 px resolution served as rear-view mirrors, providing the drivers with a 180° field of view at a distance of about 2.1 m from the driver seat. This was completed by an acoustical simulation of traffic sounds like wind and engine noises, giving the driver a rather realistic impression that can be compared to sitting in a real car.

A rural road with a recommended speed of 100 km/h served as the test track. To ensure the speed was similar for all drivers, a speed reminder was used if drivers exceeded or went below the limit by 10 km/h. The route was straight without any curves or hills, however with moderate oncoming traffic (gap sizes varied 60-100 m). No lead vehicles could be seen at the beginning of each drive. At the end of the test drive a situation with slow-moving traffic made up by nine vehicles with gap sizes of 10 m occurred. Each test drive took about two minutes including the subject-based timing evaluation concerning appropriateness and usefulness. Drivers were familiarized with the scenario beforehand.

1.2.3 Participants

In total, 24 participants (12 female, 12 male), were recruited through flyers, mailing lists, and an existing pool of trained driving simulator drivers ($M = 26.6$ years, $SD = 7.2$ years). The average driving experience was 7.6 years ($SD = 7.5$ years) and the annual mileage was mainly less than 3000 km since a big amount of drivers were university students without a car of their own. All participants had normal or corrected-to-normal visual acuity. If participants were untrained, they were invited for a first training date, lasting one hour, as the same basic driving simulator training for everyone was required for participation to avoid simulation sickness. At the actual test date, each driver received a short 20 min warm-up in order to create a similar experience with the driving simulator for all participants. Drivers were compensated with 15 € for a successful participation or received course credits (if students at the Technische Universität Braunschweig).

1.2.4 Experimental design and dependent variables

In this study, a within-subjects design was used, in which every driver selected the optimum timing of two early warning stages out of a set of seven predefined timings for two safety-critical situations (see Table 1). The critical situation varied within the two speeds of the lead vehicle (25 km/h or 50 km/h), serving as critical event at the end of each test drive and demanding different reaction times and strengths from the drivers. Each driver drove both situations in a counterbalanced order to control for time effects.

Additionally, each driver selected the optimum timing for both the first stage and the second stage of the collision warning system. As the warning strategy always consists of two combined early stages, first presenting the *information* and then the *prewarning*, the subjects

selected the optimum timing for the *information* in the first step, thus allowing a proper evaluation of the second stage. Employing this first stage's optimum timing, the second step was then to find the optimum timing for the *prewarning*. Although the drivers always experienced both stages in combination, the subject-based evaluation of the predefined timings at the end of every trial exclusively focused on one stage. According to this procedure, the two early stages of the collision warning system were evaluated as individual dependent variables.

In order to find the optimum timings, a modified version of the method of limits (Goldstein, 1996) was used, in which the drivers were presented with different timings, in either descending or ascending order, and had to rate their appropriateness and usefulness (subject-based timing evaluation). According to this method, drivers were confronted with a range of seven time-to-collision (TTC) values per stage and situation criticality as shown in Table 1, this being the time until the host vehicle will collide with the lead vehicle at the end of the slow moving traffic if none of them changes speed or course (Hayward, 1972).

Table 1 Presented TTC-ranges per first (*information*) and second warning stage (*prewarning*) in both situation criticalities (25 km/h and 50 km/h) for the subject-based timing evaluation.

Warning	Situation													
	25 km/h							50 km/h						
First stage	30	28	26	24	22	20	18	30	28	26	24	22	20	18
Second stage	18	16	14	12	10	8	6	18	16	14	12	10	8	6

On the basis of the studies of Werneke et al. (2014), the first stage was presented with TTCs varying between 30 s and 18 s. For the second stage, the range was between 18 s and 6 s (see Table 1). The order of presentation (ascending or descending) was balanced between the subjects to control for order effects. These ranges were chosen according to pretests so that the start or end TTC was mostly perceived as too early or too late, which allowed covering the optimum timing at all times, the so-called crossover point or threshold value according to Goldstein (1996).

After every presentation, drivers were asked to rate the appropriateness of each timing and its perceived benefit (usefulness) using the category-partition method (see Figure 2; Heller, 1982; Ostrand & Balcer, 1988). In a first step, drivers selected one out of the five labeled categories. In a second step, they refined their rating by choosing one out of the three subcategories (-, 0, +). This rating was then transformed into numbers from 1 to 15 ("not very useful" to "very useful"). When all seven timings out of a specific TTC set (see Table 1) were experienced and evaluated by the drivers, the TTC with the highest rating of appropriateness, being rated "*just right; 0*" on the scale, was assessed as the optimum TTC of this participant for the designated stage and situation criticality. If more than one TTC had

the same optimum rating, their average was calculated, leading to the dependent variable in the analyses. Additionally, the drivers' usefulness rating of each TTC was examined.

How was the timing of the first / second stage in this situation?

far too early			too early			just right			too late			far too late		
-	0	+	-	0	+	-	0	+	-	0	+	-	0	+

not very useful			not useful			moderate			useful			very useful		
-	0	+	-	0	+	-	0	+	-	0	+	-	0	+

Figure 2 Rating scales for the dependent variables appropriateness and usefulness of the presented TTCs (Heller, 1982).

The driving behavior was recorded in order to ensure that drivers reacted to the early warning stages in an adequate manner. However, as drivers already knew the critical situation would occur and they were very familiar with it due to the frequent repetition the applied procedure demanded, this driving behavior was certainly not representative for the typical driving behavior drivers would show in such critical situation when being warned as described. Thus, the driving data is further disregarded in favor of analyzing the subject-based evaluation data closer.

1.2.5 Test procedure

At first, participants were welcomed and instructed in written form about the objectives of the experiment. They signed a consent form and filled in a demographic questionnaire. After a short warm-up in the driving simulator, the participants received two instructions. The first described the multi-stage collision warning concept, as to pay closer attention at the first stage and beginning to reduce speed moderately in the second stage. They were then informed about the procedure to find the optimum timings as described in the section above.

To make sure the drivers had understood their task and the procedure, the collision warning system and the rating of the timings were demonstrated as well as practiced in an example trial. Each test trial always comprised the same rural road with slow-moving traffic at the end. Drivers drove a recommended speed of 100 km/h until the two early warning stages were triggered successively at the tested TTCs. After stopping the car as instructed, the currently experienced timing of the concerned stage was rated by the drivers regarding its appropriateness and usefulness (see Figure 2). This procedure was iterated for all considered TTCs (see Table 1). If a driver once missed to notice one of the early warning stages, the trial was repeated. At the end of the experiment, the instructor thanked the drivers for their participation and gave them their compensation. The entire test took one hour.

1.3 Results

1.3.1 Data analysis

For every participant, four optimum timings were assessed: one per early warning stage (first and second stage) and in both situation criticalities (25 km/h and 50 km/h lead vehicle). Subsequently, for each of the four optimum timings, the mean value over all participants was calculated. These optimum timings are first given as TTCs (in seconds) since the study of Werneke et al. (2014) had shown nearly same optimum TTCs for different speed conditions of the host vehicle. However, when analyzing the optimum stage activations in distances (in meters), in order to explore more about which criterion (time or distance) drivers consult for their rating, differences in the conditions were found. Therefore, the optimum TTC values obtained in this study were also transformed into distances (d , in meters) using the parameters speed of the host (v_h) and lead vehicle (v_l) converted from km/h into m/s by the divisor of 3.6 (see Figure 3). This computation only included the speed but not the deceleration of the host and lead vehicle, as at the time the *information* and *prewarning* were activated their speed was supposed to be nearly constant.

$$TTC = \frac{d}{(v_h - v_l)} \longrightarrow d = \frac{TTC}{3.6} (v_h - v_l)$$

Figure 3 Transformation of *time-to-collision* (TTC, in seconds) into *distance* (d , in meters) using the parameters speed of the host (v_h) and lead vehicle (v_l) converted from km/h into m/s by the divisor of 3.6.

In order to analyze the influence of the situational factor (*Situation*: 25 km/h vs. 50 km/h lead vehicle) on the optimum timing of both stages, two Wilcoxon signed-rank tests with the factor *Situation* were conducted. This was done with optimum TTCs (in seconds) and optimum distances (in meters) to replicate the effects of Werneke et al. (2014). Additionally, the usefulness was analyzed by four Friedman's ANOVAs regarding the influence of the factor *Timing* on the drivers' usefulness rating (1, "*not very useful*" to 15, "*very useful*", see Figure 2) for all experienced timings of both stages and situations. Moreover, all optimum timings were compared to the results of Werneke et al. (2014) in order to develop two linear regression functions, which allow one to estimate the optimum timing of the two early warning stages. For all data analyses, the statistical software PASW Statistics 20 was used.

1.3.2 Optimum timing and distance

The mean optimum timings and distances over all participants can be seen in Figure 4. Depending on the *Situation*, *information* (first stage) presented at approximately 447 m (SD = 34.9 m) distance to the slower lead vehicle driving at 25 km/h and at 338 m (SD = 46.4 m) distance to the faster lead vehicle driving at 50 km/h was rated as optimal (see

Figure 4, right). In the second stage, drivers chose to be prewarned about 249 m (SD = 34.5 m) ahead of the slower lead vehicle driving at 25 km/h and 186 m (SD = 36.1 m) ahead of the faster lead vehicle driving at 50 km/h (see Figure 4, right).

Regarding the optimum TTCs drivers preferred a later activation of both stages when the lead vehicle drove at 25 km/h compared to 50 km/h (see Figure 4, left). This is in contrast to the results of Werneke et al. (2014) who found nearly identical TTCs, albeit for approaching static objects. Moreover, it is somewhat contrary to intuition, as the situation with the lead vehicle traveling at 25 km/h is more critical and should require an earlier reaction of the driver. However, this seems to be due to the formula of the TTC, which becomes apparent when distance instead of TTC is used to analyze the drivers' optimum stage activations (see Figure 4, right). With regard to the optimum distances, the activation of both stages is preferred at a larger distance (meaning earlier) to the lead vehicle driving more slowly than to the faster lead vehicle. Drivers appear to not adjust this distance in the same manner as the formula of the TTC does. They seem to estimate the absolute distance rather than the time difference to approach the dynamic safety-critical object in order to find the optimum activation of these early warning stages.

Figure 4 The mean optimum *TTCs* (in seconds, left) and *distances* (in meters, right) of the host to the lead vehicle in the situations with the lead vehicle driving at 25 km/h and 50 km/h for the first (*information*) and the second stage (*prewarning*).

The inferential statistical analysis of the *Situation* influence on the optimum activation of the first stage showed a significant effect of the *Situation* with both measures (*TTC*: $z = -3.88$, $p < .001$, $r = -0.79$; *distance*: $z = -4.29$, $p < .001$, $r = -0.88$). The same holds true for the second stage (*TTC*: $z = -2.89$, $p = .004$, $r = -0.59$; *distance*: $z = -4.09$, $p < .001$, $r = -0.83$).

1.3.3 Usefulness rating

The descriptive analysis of the usefulness ratings, as can be seen in the curves of Figure 5, shows that there is an optimum usefulness of each stage in the examined situation criticalities depending on the timing. The effect of the different situation criticalities also

becomes obvious in the shift of the two curves for each stage. For example, in the situation with the 50 km/h lead vehicle the drivers' highest usefulness rating is right in the middle of the curve for both stages while decreasing towards the ends of the curves. This means the drivers' highest usefulness rating (see Figure 2) for the first stage was 11 ("useful; 0") at TTC 24 s (see Figure 5, left) and for the second stage 12 ("useful; +") at TTC 12 s (see Figure 5, right). Regarding the situation with the 25 km/h lead vehicle the drivers' highest usefulness rating for the first stage is somewhat more at the left of the diagram, being 11 ("useful; 0") at TTC 20 s (see Figure 5, left), but it might also decrease further to the left side similar to the second stage, which has its highest usefulness rating of 11 ("useful; 0") at TTC 12 s (see Figure 5, right).

Figure 5 The mean usefulness ratings of the predefined TTCs in the situations with the lead vehicle driving at 25 km/h and 50 km/h for the first (*information*, left) and the second stage (*prewarning*, right).

Moreover, the second stage curves (see Figure 5, right) are more distinct than the first stage curves (see Figure 5, left), which indicates a greater difference between the highest and the lowest usefulness ratings in the second stage. Figure 5 further allows an estimation of the relevance of the timing adaption. For example, if a usefulness rating of 10 ("useful; -") is taken as the lowest acceptable level for the timing of the early warning stages, then the timing could vary within a range of predefined TTCs; when approaching slow moving traffic driving at 50 km/h the timing of the *information* could range between 20 s and 28 s (see Figure 5, left) and for the *prewarning* between 8 s and 16 s (see Figure 5, right). Consequently, there is a stage-specific range, in which the timing of each early warning stage can vary and still be rated as useful and thus be accepted by the drivers. As Table 2 shows in addition, the assumption that the drivers' optimum timing corresponds to the timing with the drivers' highest usefulness ratings, can be confirmed for both stages and situation criticalities. For example, drivers' optimum timing for the first stage with the 50 km/h lead vehicle was at TTC 24.33 s and the predefined TTC 24 s was rated with the highest usefulness of 11 ("useful; 0") by the drivers.

Table 2 The mean optimum TTCs [s] according to the drivers' appropriateness rating and the TTCs with the drivers' highest usefulness rating out of the predefined TTCs in the situations with the lead vehicle driving 25 km/h and 50 km/h for the first (*information*) and second warning stage (*prewarning*).

Warning	Optimum timings		Timings with best usefulness	
	25 km/h	50 km/h	25 km/h	50 km/h
First stage	21.5	24.3	20.0	24.0
Second stage	12.0	13.4	12.0	12.0

The inferential statistical analysis of the *Timing* influence on the drivers' usefulness rating showed significant effects for every specific TTC set per stage and situation (*first stage with 25 km/h*: $\chi^2_{(6)} = 55.28$, $p < .001$; *first stage with 50 km/h*: $\chi^2_{(6)} = 27.55$, $p < .001$; *second stage with 25 km/h*: $\chi^2_{(6)} = 49.99$, $p < .001$; *second stage with 50 km/h*: $\chi^2_{(6)} = 61.14$, $p < .001$). A causal interpretation of these effects is not possible, as these different TTCs were not presented in random order. However, the tests were conducted to ensure that the differences found are meaningful and not due to random effects.

1.3.4 Functions to estimate the optimum activation of the early warning stages

In order to compare the results of the current study to the previous study of Werneke et al. (2014), despite their different dynamics of the safety-critical object (dynamic vs. static), the speed difference between host and lead vehicle may be a good measure for the situation criticality and thus the intensity of a required driver reaction. The previous study of Werneke et al. (2014) examined speed differences to a static lead vehicle (traffic jam) of 50 km/h, 100 km/h and 130 km/h (lead vehicle 0 km/h). In the current study the speed differences were 50 km/h (host vehicle 100 km/h, lead vehicle 50 km/h) and 75 km/h (lead vehicle 25 km/h). Since drivers have to react stronger when reducing their speed at larger speed differences, the situation criticality is accordingly higher.

Figure 6 shows the plots of the optimum distances for activation of the first and second stage for both studies. For a better interpretation of distances in meters, the speed is given in m/s. As illustrated, the optimum distances for the two stages at a speed difference of 13.9 m/s (50 km/h) are quite similar in both studies. This indicates that drivers change their optimum stage activation indeed with the speed difference regardless of whether the safety-critical object is static or dynamic. When looking at larger speed differences, there is a reasonable linear relationship between speed difference and optimum distance. However, the slope in Figure 6 is somewhat larger for the first (28.7) compared to the second stage (12.2). As the speed difference grows, drivers favor a higher increase in the optimum distance for the first compared to the second stage. However, there is some deviation from the drawn regression line. Regarding the data points for the first stage of the current study, for example, the first data point at speed difference 13.9 m/s lies quite exactly on the regression line,

whereas the second data point at speed difference 20.8 m/s obviously diverges more from the regression line. This indicated the need for further data points for such dynamic situations as examined in the current study to support the proposed functions. However, from the combined results of the two studies, the optimum *information* and *prewarning* distances in meters can be computed with the following two equations (with v given in m/s), which were calculated using a linear regression for the five mean values of each stage.

Figure 6 Linear plot and proposed regression functions of the optimum distances for the first (*information*) and the second warning stage (*prewarning*) for several speed differences (values derived from Werneke et al. (2014) are referred to as previous, values derived from this study as current).

1.4 Discussion

The driving simulator study presented here examined how the dynamics of a safety-critical object varied by its velocity (situation criticality: lead vehicle at 25 km/h or 50 km/h) influence the timing of two early warning stages of a multi-stage collision warning system (first stage: “*Informing the driver*”, second stage: “*Prewarning the driver*”). A set of predefined *information* and *prewarning* timings were evaluated by the drivers concerning their appropriateness and usefulness in order to find the optimum stage activation for both situation criticalities and to describe how the timing should be adapted accordingly (in combination with results from Werneke et al., 2014).

The analyses in the present study showed a significant effect of the dynamics of the safety-critical object (slow-moving traffic ahead) on the designed early warning stages of the collision warning system. As expected, drivers traveling at 100 km/h preferred both early warning stages at a greater distance in the situation with a slower lead vehicle compared to the situation with a faster lead vehicle. This shows the drivers’ ability to differentiate between the two situation criticalities. Obviously, drivers are aware of the situation-specific reaction time and strength demand respectively due to the higher speed reduction required by them in

the situation with the larger speed difference, which thereby bears a greater situation criticality.

At first, the analysis of the optimum TTCs (in seconds) for the two early warning stages of the collision warning system was contra-intuitive. Drivers significantly preferred to be informed and prewarned later in the more critical situation (lead vehicle driving at 25 km/h) although drivers had to react earlier or sturdier. However, when transforming TTCs into distances (in meters) the direction of the effect changed in a more reasonable way. In the above-mentioned study of Werneke et al. (2014), it seemed that drivers mentally computed the time they needed to come to a standstill and prevent a collision with the static safety-critical object. That is why TTCs were also used in this study, but the assumed formula of TTC apparently is not applicable to describe what drivers mentally do when the safety-critical object is dynamic as in the present study. Here, drivers seem to employ the distance to the safety-critical object as their reference for the activation of the early warning stages. Accordingly, in combination with the results of Werneke et al. (2014), a linear relationship between the speed difference and the distance to the safety-critical object (as indicator for the *information* and *prewarning* activation) seems to describe both data sets rather well. From a psychological point of view, the perception of distance is one of the fundamental characteristics of visual perception (Goldstein, 1996) and thus it seems reasonable that drivers use this ability instead of mentally computing TTC. In line with this reasoning, many studies showed that drivers have difficulties estimating TTCs properly (e.g., Cavallo & Laurent, 1988; McLeod & Boss, 1983; Schiff & Detwiler, 1979). Beyond that, various further variables influence drivers' TTC perception like optic flow rates, contrast levels, depth cues and external factors such as driving experience, age and even gender also correlate with the TTC estimation accuracy (for further discussion see Gray & Regan, 1999; Green, Allen, Abrams, & Weintraub, 2008; Lee, 1976; Van der Horst, 1990).

With regard to the optimum distances, drivers preferred to be informed (first stage) at nearly 450 m in the more critical situation (lead vehicle driving at 25 km/h), while at nearly 340 m in the less critical situation (lead vehicle driving at 50 km/h), which amounts to a difference of approximately 110 m. This difference, although a bit smaller, was also shown for the second stage, here drivers preferred to be prewarned approximately 65 m later in the less critical situation (at 185 m) than in the more critical one (at 250 m).

Another interesting finding is that the optimum distances selected by the drivers are much larger than distances computed using typical human reaction and decelerating times. For example, Tang and Yip (2010) found optimum distances for warnings similar to the here examined second stage warning (intended to elicit moderate brake reactions) of approximately 140 m and 110 m for a vehicle driving with 110 km/h in good road conditions and encountering a standing vehicle or a vehicle driving with 60 km/h. Under poorly

maintained road conditions this changed to larger distances of nearly 190 m and 150 m. These optimum distances were computed based on typical driver reaction times and braking distances. However, the present study lets the drivers adjust their optimum themselves. This way, the second stage was preferred at more than 300 m and 185 m under normal road conditions, which indicates that drivers prefer more time to prepare for such situations than has so far been calculated by technical computations in the literature. This difference might also be affected by further details unique to this study. For instance, most other studies do not use driver *information* as a first stage of a multi-stage warning system, which might influence the general perception of the activation distances. Additionally, the study was conducted in a driving simulator, in which speed estimations are more difficult than in real traffic (Cavallo, Mestre, & Berthelon, 1997; Sidaway, Fairweather, Sekiya, & McNitt-Gray, 1996).

Furthermore, regarding the large distances used to activate the two early warning stages in the present study, a very high resolution of the driving simulator is needed to allow drivers a good object perception. The resolution of 1400 x 1050 px used in this study might have been challenging. However, it was ensured that the vehicles in front were well visible and that the drivers knew the scenario before actually evaluating the optimum timings. Moreover, drivers in this study did not have to be able to detect a slow-moving vehicle in all its details but to estimate the distance to it accurately. Several cues which humans use to perceive depth are very well presented in the driving simulator (e.g., size of the objects, texture gradients etc.), yet the view was not as well as in the real world. Therefore it would be interesting to compare the results to real world estimates. On the other hand, only the simulator enables to systematically vary the factor stage timing or distance respectively this accurately while encountering the same traffic jam over and over again. In conclusion, despite the mentioned challenges like the object perception, constructing this experiment in the simulator is still advantageous, since it offers constant conditions and helps to easily obtain this kind of subject-based data.

Another restriction to the results might lie in the number of repetitions per scenario, leading to fatigue and reduced motivation of the drivers due to monotony effects, which was a trade-off for using a constant and well-known scenario to compare both situation criticalities. The control questionnaire on the drivers' condition (including fatigue as item) before and after the test though did not show any significant influences of this time issue. The continuous scenario repetition might still have let the situations appear less realistic to the drivers. Consequently, even though there are limits to the study's external validity, its results demonstrate a meaningful contribution to the question when to activate early collision warnings since they are so far little investigated, especially in this style, by using a multi-stage warning strategy and above all including the drivers' perspective this much.

Moreover, the study of Tang and Yip (2010) also pointed out that braking maneuvers differ depending on the current road conditions. Varied road conditions might as well result in different optimum timings and distances respectively. Thus, it would be interesting to consider further situational influences like weather conditions as rain or snow on the optimum timing of the early warning stages. Additionally, the study should be extended to further groups with different age and driving experience.

Furthermore, drivers' usefulness ratings of the presented timings were used to assess drivers' acceptance. The usefulness ratings for each stage and situation criticality varied with the presented timings, although slightly more distinct in the second stage than in the first stage. This is according to assumptions as the second stage necessitates a stronger and faster reaction from the drivers. Adapting the timing to the drivers' preferences thus might be somewhat more important for the *prewarning* (second stage) than for the *information* (first stage), although for both stages the timing could vary within a range of 8 s width and would still be acceptable for drivers. In addition, the timings with the best drivers' usefulness ratings out of each presented TTC set corresponded to the optimum timings based on the drivers' appropriateness ratings as expected. Thus, the results of the drivers' usefulness ratings underpin the idea that the timing of such early warning stages is crucial for drivers' acceptance and thus the use of the warning system in general.

The results have also shown that the optimum timings to activate the early warning stages do not differ considerably between static and dynamic (25 km/h and 50 km/h) safety-critical objects when computing the optimum timings in distances, as the comparison to the study of Werneke et al. (2014) illustrated. The speed difference seems to be the most crucial factor for the adaptation of warning timings since adjusting speed or braking takes longer at larger speed differences. Thus, a variation of the speed difference should result in varied optimum distances for activating *information* or *prewarnings*. Accordingly, the optimum distances for both stages seem to depend on the speed difference between the host and the lead vehicle or safety-critical object in a linear manner.

For the range of 50 km/h to 130 km/h (13.9 m/s to 36.1 m/s) two linear regression equations are provided by combining the results of Werneke et al. (2014) and this study, which give the optimum distances to activate the early warning stages according to drivers' evaluation. They can be used in driver assistance systems to compute the optimum activation of the respective early warning stages, but have to be handled with care due to the limited number of data points (especially for the dynamic situation). Further data points might contradict the proposed linearity or show less alignment between the static and the dynamic object situation. It would be interesting to see if this linear relationship could be transferred to lower speed differences, for example, when driving at low speed (like 50 km/h) and approaching a slightly slower car (like 25 km/h). For very small speed differences the concept

of early warning stages might not be valid any longer as these occur constantly during car following, but it is still unclear where this limit lies exactly. Moreover, both studies varied speed differences and the dynamics of the safety-critical object, but disregarded other aspects like the type of the safety-critical object, even though the drivers' preferences might differ when other objects like pedestrians or cyclists are concerned. Concluding, further studies should examine this range of speed differences, as extrapolations are always difficult.

Summing up, the method used here of finding the optimum timing and judging its usefulness by a subject-based driver evaluation was convenient and should be applied for further research, since it includes the drivers into the design process (at an early stage). Additionally, this study underpins the importance of the timing of driver warnings (especially early warning stages) for the drivers' acceptance and how essential situational factors are when adapting this timing. Many more situational factors (e.g., rain or driver-concerned, drivers' age) should be considered and tested when optimizing driver warnings and their timing. In this regard, the proposed functions describing the adequate timing of the two early warning stages depending on the speed difference to the safety-critical object are useful in the frequently occurring case of the safety-critical object being a slower or standing vehicle. It would be interesting to see in which way this is applicable to other critical collision situations.

1.5 References

- Abe, G., & Richardson, J. (2006). Alarm timing, trust and driver expectation for forward collision warning systems. *Applied Ergonomics*, 37, 577-586, <https://doi.org/10.1016/j.apergo.2005.11.001>.
- Bella, F., & Russo, R. (2011). A Collision Warning System for rear-end collision: a driving simulator study. *Procedia Social and Behavioral Sciences*, 20, 676-686, <https://doi.org/10.1016/j.sbspro.2011.08.075>.
- Brown, T. L., Lee, J. D., & McGehee, D. V. (2001). Human performance models and rear-end collision avoidance algorithms. *Human Factors*, 43(3), 462-482, <https://doi.org/10.1518/001872001775898250>.
- Campbell, J. L., Richard, C. M., Brown, J. L., & McCallum, M. (2007). *Crash Warning System Interfaces: Human Factors Insights and Lessons Learned* (Report No. DOT HS 810 697). Washington, DC, USA: National Highway Traffic Safety Administration (NHTSA). Retrieved from https://www.nhtsa.gov/DOT/NHTSA/NRD/Multimedia/PDFs/Crash%20Avoidance/2007/CWS_HF_Insights_Task_5_Final_Rpt.pdf
- Cavallo, V., & Laurent, M. (1988). Visual information and skill level in time-to-collision estimation. *Perception*, 17(5), 623-632, <https://doi.org/10.1068/p170623>.
- Cavallo, V., Mestre, D., & Berthelon, C. (1997). Time-To-Collision Judgements: Visual and Spatio-Temporal Factors. In J. A. Rothengatter, & E. Carbonell Vaya (Eds.), *Traffic and Transport Psychology: Theory and Application* (pp. 97-111). Amsterdam, The Netherlands: Pergamon Press.

- Geiser, G., & Nirschl, G. (1993). Towards a system architecture of driver's warning assistant. In A. M. Parkes & S. Franzen (Eds.), *Driving Future Vehicles* (pp. 251-263). London, UK: Taylor and Francis.
- General Motors Corporation, & Delphi-Delco Electronic Systems (2002). *Automotive Collision Avoidance Operational Field Test Warning Cue Implementation Summary Report* (DOT HS 809 462). Washington D. C., US: National Highway Transportation Safety Administration. Retrieved from ece.eng.wayne.edu/~smahmud/CrashAvoidance/WarningDisplay02.pdf
- Goldstein, E. B. (1996). *Sensation and Perception* (4th edition). Pacific Grove, CA, USA: Brooks/Cole.
- Gray, R., & Regan, D. (1999). Adapting to expansion increases perceived time-to-collision. *Vision Research*, 39, 3602-3607, [https://doi.org/10.1016/S0042-6989\(99\)00065-6](https://doi.org/10.1016/S0042-6989(99)00065-6).
- Green, M., Allen, M. J., Abrams, B. S., & Weintraub, L. (2008). *Forensic Vision: With Application to Highway Safety* (3rd edition). Tucson, AZ, USA: Lawyers and Judges Publishing.
- Hayward, J. Ch. (1972). Near miss determination through use of a scale of danger. *Highway Research Record*, 384, 24-34.
- Heller, O. (1982). Theorie und Praxis des Verfahrens der Kategorienunterteilung (KU). In O. Heller (Ed.), *Forschungsbericht 1981* (pp. 1-15). Würzburg, Germany: Psychologisches Institut der Universität Würzburg.
- Hiraoka, T., Nakata, K., Tanaka, M., & Kumamoto, H. (2008). Situation-adaptive warning timing of a forward obstacle collision warning system. In *Proceedings of the 15th World Congress on Intelligent Transport Systems and ITS America Annual Meeting* (pp. 5576-5587). New York, NY, USA.
- Horowitz, A. D., & Dingus, T. A. (1992). Warning signal design: a key human factors issue in an in-vehicle front-to-rear-end collision warning system. In *Proceedings of the Human Factors Society 36th Annual Meeting* (pp. 1011-1013). Santa Monica, CA, US: Human Factors and Ergonomics Society.
- Jones, E. M., & Hansman, R. J. (2007). Approaches to Enhance Driver Situational Assessment Aids (ICAT-2007-3). Retrieved from <http://hdl.handle.net/1721.1/38869>.
- Jamson, A. H., Lai, F. C. H., & Carsten, O. M. J. (2008). Potential Benefits of an Adaptive Forward Collision Warning System. *Transportation Research Part C: Emerging Technologies*, 16(4), 471-484, <https://doi.org/10.1016/j.trc.2007.09.003>.
- Janssen, W., & Nilsson, L. (1993). Behavioural effects of driver support. In A. M. Parkes, & S. Franzen (Eds.), *Driving Future Vehicles* (pp. 147-155). London; UK: Taylor and Francis.
- Krüger, H.-P., Grein, M., Kaussner, A., & Mark, C. (2005). SILAB – A task-oriented driving simulation. In *Proceedings of the Driving Simulator Conference* (pp. 232-331). Iowa City, IA, USA.
- Lee, D. N. (1976). A theory of visual control of braking based on information about time-to-collision. *Perception*, 5(4), 437-459, <https://doi.org/10.1068/p050437>.
- Lee, J. D., & Kantowitz, B. H. (1998). Perceptual and cognitive aspects of intelligent transportation systems. In W. Barfield, & T. A. Dingus (Eds.), *Human Factors in Intelligent Transportation Systems* (pp. 31-54). London, UK: Lawrence Erlbaum Associates.
- Lee, J. D., McGehee, D. V., Brown, T. L., & Reyes, M. L. (2002). Collision warning timing, driver distraction, and driver response to imminent rear-end collisions in a high-fidelity

- driving simulator. *Human Factors*, 44(2), 314-334, <https://doi.org/10.1518/0018720024497844>.
- Lenné, M. G., Triggs, T. J., Mulvihill, C. M., Regan, M. A., & Corben, B. F. (2008). Detection of emergency vehicles: Driver responses to advance warning in a driving simulator. *Human Factors*, 50(1), 135-144, <https://doi.org/10.1518/001872008X250557>.
- Lenné, M. G., & Triggs, T. J. (2009). Warning drivers of approaching hazards: The importance of location cues and multi-sensory cues. In D. De Waard, J. Godthelp, F. L. Kooi, & K. A. Brookhuis (Eds.), *Human Factors, Security and Safety* (pp. 203-211). Maastricht, The Netherlands: Shaker Publishing.
- Lerner, N., Dekker, D., Steinberg, G., & Huey, R. (1996). *Inappropriate alarm rates and driver annoyance* (Report No. DOT HS 808 533). Washington, DC, USA: National Highway Traffic Safety Administration (NHTSA). Retrieved from http://ntl.bts.gov/lib/jpodocs/repts_te/3757.pdf
- McGehee, D. V., Brown, T. L., Lee, J. D., & Wilson, T. B. (2002). Effect of warning timing on collision avoidance behavior in a stationary lead-vehicle scenario. *Transportation Research Record*, 1803(1), 1-6, <https://doi.org/10.3141/1803-01>.
- McLeod, R. W., & Boss, H. E. (1983). Optic-flow and cognitive factors in time-to-collision estimates. *Perception*, 12(4), 417-423, <https://doi.org/10.1068/p120417>.
- Ervin, R. D. (2005). *Automotive collision avoidance system – field operational test report: Methodology and Results* (Report No. DOT HS 809 900). Washington, DC, USA: National Highway Traffic Safety Administration (NHTSA). Retrieved from <http://hdl.handle.net/2027.42/49539>.
- Naujoks, F., & Neukum, A. (2014). Timing of in-vehicle advisory warnings based on cooperative perception. In D. de Waard, K. A. Brookhuis, R. Wiczorek, F. di Nocera, R. Brouwer, P. Barham, C. Weikert, A. Kluge, W. Gerbino, & A. Toffetti (Eds.), *Proceedings of the Human Factors and Ergonomics Society Europe Chapter 2013 Annual Conference* (pp. 193-206). Retrieved from <http://www.hfes-europe.org/wp-content/uploads/2014/06/Naujoks.pdf>.
- Naujoks, F., & Totzke, I. (2014). Behavioral adaptation caused by predictive warning systems - The case of congestion tail warnings. *Transportation Research Part F: Traffic Psychology and Behaviour*, 26, 49-61, <https://doi.org/10.1016/j.trf.2014.06.010>.
- Neukum, A. (2011). Wenn das Fahrzeug mehr sieht als der Fahrer – Konsequenzen für die Gestaltung der Fahrer-Fahrzeug Schnittstelle. Paper presented at the Ko-FAS Zwischenpräsentation, Schloss Aschaffenburg, Aschaffenburg, Germany.
- Ostrand, T. J., & Balcer, M. J. (1988). The category-partition method for specifying and generating functional tests, *Communications of the ACM*, 31(6), 676-686, <https://doi.org/10.1145/62959.62964>.
- Parasuraman, R., Hancock, P. A., & Olofinboba, O. (1997). Alarm effectiveness in driver-centered collision warning systems. *Ergonomics*, 40(3), 390-399, <https://doi.org/10.1080/001401397188224>.
- Petermann-Stock, I., & Rhede, J. (2013). Intelligent strategies for user-centered MMI concepts in urban space. In *VDI-Wissensforum (Ed.), Der Fahrer im 21. Jahrhundert. Fahrer, Fahrerunterstützung und Bedienbarkeit. VDI Berichte Nr. 2205* (pp. 263-286). Düsseldorf, Germany: VDI.
- Popiv, D., Rommerskirchen, C., Bengler, B., Duschl, M., & Rakic, M. (2010). Effects of assistance of anticipatory driving on drivers' behavior during deceleration phases. In J. Krems, T. Petzold, & M. Henning (Eds.), *European Conference on Human Centered*

- Design for Intelligent Transport Systems* (pp. 133-145). Lyon, France: HUMANIST Publications.
- Posner, M. I., Klein, R., Summers, J., & Buggie, S. (1973). On the selection of signals. *Memory and Cognition*, 1, 2-12, <https://doi.org/10.3758/BF03198062>.
- Raksincharoensak, P. & Nagai, M. (2008). Forward Collision Warning Algorithm based on road condition and driver characteristics. In *Proceedings of the 15th World Congress on Intelligent Transport Systems and ITS America Annual Meeting* (pp. 2993-3001). New York, NY, US.
- Reichart, G. (1993). Human and technical reliability. In A. M. Parkes, & S. Franzen (Eds.), *Driving Future Vehicles* (pp. 409-418). London, UK: Taylor and Francis.
- Rhede, J., Waller, C., & Oel, P. (2011). Der FAS-Warnbaukasten. Strategie fur die systematische Entwicklung und Ausgabe von HMI-Warnungen. In VDI-Wissensforum (Ed.), *Der Fahrer im 21. Jahrhundert. Fahrer, Fahrerunterstutzung und Bedienbarkeit. VDI Berichte Nr. 2134* (pp. 63-74). Dusseldorf, Germany: VDI.
- Rogers, W. A., Lamson, N., & Rousseau, G. K. (2000). Warning research: An integrative perspective. *Human Factors*, 42(1), 102-139, <https://doi.org/10.1518/001872000779656624>.
- Schiff, W., & Detwiler, M. L. (1979). Information judged in impending collision. *Perception*, 8(6), 647-658, <https://doi.org/10.1068/p080647>.
- Schmidt, G. (2012). *The Influence of Anticipation and Warnings on Collision Avoidance Behavior of Attentive Drivers*. Ph.D. Thesis, Julius-Maximilians-Universitat Wurzburg, Wurzburg, Germany.
- Seiler, P., Song, B., & Hedrick, J. K. (1998). Development of a collision avoidance system. *Automotive Engineering International*, 106(9), 24-28.
- Shannon, C. E., & Weaver, W. (1976). *Mathematische Grundlagen der Informationstheorie*. Munchen, Wien: Oldenbourg.
- Sidaway, B., Fairweather, M., Sekiya, H., & McNitt-Gray, J. (1996). Time-to-Collision Estimation in a Simulated Driving Task. *Human Factors*, 38(1), 101-113, <https://doi.org/10.1518/001872096778940813>.
- Spence, C., & Ho, C. (2008). Multisensory warning signals for event perception and safe driving. *Theoretical Issues in Ergonomics Science*, 9(6), 523-554, <https://doi.org/10.1080/14639220701816765>.
- Tan, H.-S., & Huang, J. (2006). DGPS-Based Vehicle-to-Vehicle Cooperative Collision Warning: Engineering Feasibility Viewpoints. *IEEE Transactions on Intelligent Transportation Systems*, 7(4), 415-428, <https://doi.org/10.1109/TITS.2006.883938>.
- Tang, A., & Yip, A. (2010). Collision avoidance timing analysis of DSRC-based vehicles. *Accident Analysis & Prevention*, 42, 182-195, <https://doi.org/10.1016/j.aap.2009.07.019>.
- Totzke, I., Naujoks, F., & Muhlbacher, D. (2011). Warnungen vor Stauenden: Nutzen Fahrer prazise Positionsangaben bei Stauendewarnungen? [Traffic jam ahead warning: Do drivers need information of the position of the traffic jam?]. In Intelligente Transport- und Verkehrssysteme und -dienste Niedersachsen e.V. (Ed.) *AAET-Automatisierungssysteme, Assistenzsysteme und eingebettete Systeme fur Transportmittel* (pp. 79-97). Braunschweig, Germany: ITS Niedersachsen.
- Van der Horst, A. R. A. (1990). *A Time-Based Analysis of Road User Behavior in Normal and Critical Encounters*. Ph.D. Thesis, Technische Universiteit Delft, Delft, The Netherlands.
- van Driel, C. J. G., Hoedemaeker, M., & van Arem, B. (2007). Impacts of a congestion assistant on driving behaviour and acceptance using a driving simulator. *Transportation*

- Research Part F: Traffic Psychology and Behaviour*, 10(2), 139-152, <https://doi.org/10.1016/j.trf.2006.08.003>.
- Weiß, C. (2011). V2X communication in Europe – From research projects towards standardization and field testing of vehicle communication technology. *Computer Networks*, 55(14), 3103-3119, <https://doi.org/10.1016/j.comnet.2011.03.016>.
- Werneke, J., Wäller, C., Gonter, M., Rhede, J., & Vollrath, M. (2011). Evaluation eines integrierten Warnkonzepts für unterschiedliche Fahrsituationen. In *VDI-Wissensforum (Ed.), Der Fahrer im 21. Jahrhundert. Fahrer, Fahrerunterstützung und Bedienbarkeit. VDI Berichte Nr. 2134* (pp. 93-104). Düsseldorf, Germany: VDI.
- Werneke, J., Kleen, A., & Vollrath, M. (2014). Perfect timing – Urgency, not driving situations influence the best timing to activate warnings. *Human Factors*, 56(2), 249-259, <https://doi.org/10.1177/0018720813490728>.
- Winkler, S., Kazazi, J., & Vollrath, M. (2016). Driving with a multi stage warning system in the head-up display – How do drivers react upon it? In D. de Waard, K. A. Brookhuis, A. Toffetti, A. Stuiver, C. Weikert, D. Coelho, D. Manzey, A. B. Ünal, S. Röttger, & N. Merat (Eds.), *Proceedings of the Human Factors and Ergonomics Society Europe Chapter 2015 Annual Conference* (pp. 141-153). Retrieved from <http://www.hfes-europe.org/wp-content/uploads/2015/12/Winkler2016.pdf>
- Wogalter, M. (2006). *Handbook of warnings*. Mahwah, NJ, USA: Lawrence Erlbaum Associates.
- Zarife, R. (2014). *Integrative Warning Concept for Multiple Driver Assistance Systems*. Ph.D. Thesis, Julius-Maximilians-Universität Würzburg, Würzburg, Germany