Timing of in-vehicle advisory warnings based on cooperative perception

Frederik Naujoks & Alexandra Neukum
Centre for Traffic Sciences (IZVW), University of Wuerzburg
Germany

Abstract

Future cooperative perception technologies provide the possibility of assisting drivers by so-called advisory warnings in potentially dangerous driving situations. The effectiveness of such advisory warnings will possibly depend on (1) warning timing and (2) situation-specific expectations of the driver. Using a fixed-base driving simulator, n=20 participants encountered three different conflict situations, which varied in the possibility to anticipate critical situations: (1) turning vehicle taking the driver’s right of way (anticipation level: low), (2) pedestrian entering the road between parked cars (anticipation level: medium) and (3) cyclist passing a signalized intersection (anticipation level: high). The situations were completed with and without assistance by a prototypical advisory warning system. Advisory warnings were provided via head-up-display and accompanied by an unobtrusive acoustic signal. Warning timing was varied in five steps (last possible warning moment up to four seconds prior to the last possible warning moment in 1s-steps). Advisory warnings strongly reduced objective and subjective situation criticality if they were provided at least one second before the last possible warning moment, whereas drivers subjectively preferred advisory warnings between two and three seconds before. The advisory warnings were of greatest effect when conflict situations were hard to anticipate.

Introduction

The Ko-PER research project aims at achieving improvement in preventive traffic safety. Ko-PER is a German national research project, which is founded by the Federal Ministry of Economics and Technology. Its objective is to use distributed sensory networks in order to provide road users with a complete picture of the local traffic environment. Here, wireless vehicle-vehicle and vehicle-infrastructure communication is used to provide information about the current traffic situation and to consolidate it with vehicle-localized environmental perception (so-called cooperative perception). Thus, in comparison to sensor systems that are only vehicle-localized, conflict situations can be detected more completely (e.g., by eliminating sight obstructions) and much earlier, which enables on-time driver support. Functional and HMI development run parallel during the Ko-PER research project. The objective of the HMI design is to determine suitable information
strategies in order to provide early driver assistance in impending and time-critical conflict situations.

This paper presents the results of a simulator study during which advisory warnings were provided before critical traffic situations in order to mitigate conflict. Based on research results pertaining to imminent crash warnings, it is expected that the effectiveness of such advisory warnings on one hand depends on the time of transmission of such data to the driver, and on the other hand is contingent upon the situation-specific expectation by the driver (Schmidt & Krüger, 2011); that is to say, the driver having the option to react in anticipation of conflict situations.

**Background**

**Motivation**

The basis for the output of an information or a warning signal is so-called ‘situation analysis’ (Weidl & Breuel, 2012). Here, based on the consolidated data of the cooperative perception, current traffic situations are captured holistically and a probabilistic situation prognosis, including a forecasting situation criticality, are generated. The assessment of the prognosticating situation criticality (e.g., via a time-based measure such as Time-to-collision) is utilized in order to prioritize the type of driver assistance (e.g., advisory warning at (still) low-level situation criticality or imminent crash warning at high prognosticated situation criticality). The challenge when designing early advisory warnings is the decision regarding the transfer of potentially unreliable information to the driver. Although, from a technical point of view, it is possible to collect these data, based on its probabilistic nature, it might be unreliable, and therefore may have a negative effect on the efficiency and acceptance of the driver support (Bliss & Acton, 2003; Sorkin, 1988). Based on findings regarding urgent warnings (Brown, Lee & McGehee, 2001; Lee, McGehee, Brown & Reyes, 2002; McGehee, Brown, Lee & Wilson, 2002) the *time frame for advisory warnings* must be localized. In order to ensure maximum reliability and, at the same time, ascertain a minimum degree of distraction, advisory warnings should be provided as late as possible, but as early as needed in order to initiate an adequate driver’s response. However, currently, information about this time frame, which represents an important foundation for the design of the HMI, is only available in isolated cases (e.g., Lenné & Triggs, 2009; Totzke, Naujoks, Mühlbacher & Krüger, 2012) but was prepared within the scope of the study at hand.

**Conceptual framework**

Established concepts to provide driver assistance in impending conflict situations are largely based on vehicle-localized sensor systems and are considered to render urgent driver warning signals in order to prevent collisions or, if necessary, autonomously intervene with the operation of the vehicle (e.g., Brown et al., 2001; Rhede, Wäller & Oel, 2011; Winner, 2009). Pertinent review articles consider intervals of 700 to 1,500 ms prior to an imminent accident as a suitable time frame for such urgent warnings (referred to as ‘imminent crash warnings’, e.g., Lenné & Triggs, 2009; Spence & Ho, 2008). When considering cooperative perception, the
time frame prior to the imminent crash warnings (> 1,500 ms), makes the presentation of driver information about impending conflict situations accessible (Neukum, 2011). These messages referred to as ‘advisory warnings’ (Lenné & Triggs, 2009) or ‘risk information’ (Rhede et al., 2011) should alert the driver to a potential conflict and render him/her ready to respond. On the contrary, imminent crash warnings aim at the immediate reaction of the driver in order to avoid a collision. During the Ko-PER conception phase of the driver assistance system, it was assumed that the established chronological warning structures, that have been described or investigated many times, should be maintained in order to ensure a consistent message transfer to the driver. Therefore, the chronological structure of the warning concepts that are based on vehicle-localized sensor systems will be supplemented by adding an early information component (i.e., advisory warnings) by means of a cooperative sensor system without changing previous chronological structures of established warning concepts (i.e., imminent crash warnings, see Figure 1).

Figure 1. Schematic of a time frame for driver assistance during the last seconds prior to a collision (Neukum, 2011).

Configuration of advisory warnings for collision avoidance

In addition to the point in time when to provide effective advisory warnings, which is the focus of this study, a decision must be made concerning the modality and content of the information provided. In part, this may be based on available research papers. From the literature pertaining to the configuration of advisory warnings, the following recommendation for the modality design can be derived (e.g. Campbell, Carney & Kantowitz, 1997; COMSIS Corporation, 1996; Dingus, Jahns, Horowitz & Knipling, 1998; Green, Levison, Paelke & Serafin, 1993; International Harmonized Research Activities (IHRA) working group on Intelligent Transport Systems (ITS), 2008; Rhede et al., 2011):

- Application of visual displays rather than voice messages or exigent sounds.
- Acoustic signals (warning sounds or audio response) are to be avoided and should be reserved only for urgent warnings. This applies in particular to frequent activation that may cause false alarms (which is to be expected for
early advisory warnings). These urgent auditory warnings may have an adverse effect in this case.

- An announcement that uses a non-intrusive tone can increase the effectiveness of the advisory warning.

Furthermore, additional requirements for the content of the advisory warning can be derived from the above-mentioned configuration recommendations. It is recommended to further display the type of the respective conflict (referred to as conflict specificity) and the location at which the conflict is imminent (referred to as directional specificity). It is further conceivable to provide information about the distance remaining to the imminent conflict (referred to as location specificity) or providing data about the predicted probability of the conflict (referred to as risk specificity). Whether such specific data stimulate a favorable effect on driving behaviour in imminent conflict situations cannot be conclusively explained based on the available literature. There are studies that provide information about a faster driver response when provided with directional-specific signals (Ho & Spence, 2005; Spence & Ho, 2008; 2009) as well as studies that do not provide evidence for the benefits of such signals (Lee, Gore & Campbell, 1999; Bliss & Acton, 2003; Cummings, Kilgore, Wang & Kochhar, 2007). With regard to the effectiveness of conflict (Cummings, Kilgore, Wang & Kochhar, 2007; Thoma et al., 2009), local (Totzke et al., 2012), and risk-specific (Gupta, Bisantz & Singh, 2002; Lee, Hoffman & Hayes, 2004) warnings, there are very few studies with mixed results. Therefore, positive statements about the benefits of such warnings cannot be supported conclusively.

**Method**

*Experimental design*

The sample consisted of N = 20 participants, half of them male and half of them female of various age groups (20-39 years of age: N=10, 50-71 years of age: N=10). At the time of the study, the driving experience of the participants varied between two and 53 years (M = 28.10 years, SD = 17.29 years). The participants were selected from an existing WIVW (Wuerzburg Institute for Traffic Sciences) test driver panel. All participants had previously participated in extensive simulator training.

The study was conducted in the WIVW static driving simulator using a within-subject design with the experimental factors (1) warning timing and (2) situation-specific expectations of the driver. Supplied with or without driver assistance, the participants manoeuvred through a simulator course that included different conflict situations. Advisory warnings about upcoming conflicts were provided up to four seconds prior to the last possible warning moment and in five increments. The second focus of this study was a selection of three conflict situations (see Table 1).

Here, the degree of predictability of conflicts varied. In an anticipated situation, a cyclist crosses the road while the vehicle attempts a right-hand turn (high anticipation). In an unexpected scenario, a pedestrian appears between two parked vehicles, enters the road and crosses it (medium anticipation). In a surprising situation, a turning vehicle ignores a stop sign, disregarding the right of way of the
participant (low anticipation). In order to control sequence effects, six different random scenario orders were created and assigned to the drivers at random. Furthermore, the simulator course included several non-critical scenarios in which no driver intervention was needed.

**Human machine interface**

The drivers received visual-auditory advisory warnings, which contained the respective display of the opposing road user and the direction of the conflict. In combination with an unobtrusive acoustic signal (500 Hz sinus), it was displayed in the simulated HUD (see Table 1). The point in time when the advisory warning was provided was varied in five stages, whereby one second was added to the last possible warning moment \( t_0 \) (see Table 1). Under consideration of the initial speed, it was assumed that after receiving the information, the driver activates the brakes after a reaction time \( T_r \) of one second and continues deceleration at \( 8 \, \text{m/s}^2 \) until the vehicle comes to a complete halt: \( t_0 = T_r + (v/2a) \) whereby: \( T_r = 1 \, \text{s}, \, a = -8 \, \text{m/s}^2 \).

Triggering the advisory warning was a function of the driver’s behaviour. The remaining time to reach the respective conflict point\(^1\) was taken into consideration. If during this phase the respective threshold time \( t_0, t_{0+1}, \text{etc.} \) fell short, the advisory warning was triggered. If the driver initiated the deceleration when approaching the point of conflict, no advisory warning was provided.

**Table 1. Scenarios, HUD displays, and time of warning presentation as a function of the respective driving speed.**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>( v ,[\text{km/h}] )</th>
<th>( t_0 )</th>
<th>( t_{0+1} )</th>
<th>( t_{0+2} )</th>
<th>( t_{0+3} )</th>
<th>( t_{0+4} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anticipated: Right turn – crossing cyclist at traffic light</td>
<td>25</td>
<td>1.43</td>
<td>2.43</td>
<td>3.43</td>
<td>4.43</td>
<td>5.43</td>
</tr>
<tr>
<td>Unexpected: Pedestrian enters the road between parked cars</td>
<td>50</td>
<td>1.87</td>
<td>2.87</td>
<td>3.87</td>
<td>4.87</td>
<td>5.87</td>
</tr>
<tr>
<td>Surprising: Turning vehicle takes right of way</td>
<td>50</td>
<td>1.87</td>
<td>2.87</td>
<td>3.87</td>
<td>4.87</td>
<td>5.87</td>
</tr>
</tbody>
</table>

\(^1\) Time to the point of conflict \( [\text{s}] \) = Distance to the point of conflict \( [\text{m}] \) / speed \( [\text{m/s}] \)
Dependent variables

In addition to the recording of objective data, e.g., approaching and deceleration behaviour of the driver during conflict situations, subjective assessments of the experienced criticality (Neukum et al., 2008; Figure 2 left) were raised. Furthermore, the participants rated the extent to which they experienced the situation as surprising, how timely the information was presented and how helpful the information was (Figure 2).

![Figure 2. Subjective measures.](image)

Statistical procedures

Given the experimental setup (within-subject design), global effects of the independent variables (scenario: low vs. medium vs. high anticipation of critical driving scenario, level/timing of driver assistance: no assistance vs. advisory warning at t_0 vs. … advisory warning at t_{0+4s}) on driving behaviour and subjective assessments were investigated using linear mixed models (fixed effects: scenario, timing and interaction scenario x timing; random effect: participants) with an alpha level of 5%. Differences in subjective and objective situation criticality to unassisted driving were of special interest in this study. Here, t-tests for dependent samples were applied in order to test for significant differences to baseline driving.

Results

As is evident in Table 2, most participants fell below the trigger threshold for advisory warnings pertaining to the surprising and unexpected situation. During the anticipated situation, the participants reduced their speed by themselves and, therefore, triggered a late advisory warning (t_0 unt t_{0+1s}) less frequently.

![Table 2. Frequency of triggering advisory warnings.](image)
Consequently, the intended manipulation of the predictability of the situations was being fulfilled. This was also substantiated in the subjective assessment of level of surprise in the conflict situations (see Table 3) during baseline drives without driver assistance. On average, the surprising situation was rated as ‘surprising’, the unexpected situation as ‘medium surprising’ and the anticipated situation as ‘little surprising’. The impact of advisory warnings depended on the warning timing and the respective situation (scenario: $F = 14.13$, $p < .001$; timing: $F = 11.78$, $p < .001$; interaction: $F = 2.84$, $p = .009$). When considering the surprising and the unexpected situation, it becomes clear that, compared to non-assisted driving, the situations were consistently assessed as less surprising from $t_{0+2s}$ (in the unexpected scenario) or $t_{0+1s}$ (in the surprising scenario, see Table 3). On the contrary, the anticipated situation was little surprising without and with driver assistance.

Table 3. $T$-test for dependent sample statistics, difference to baseline in participants’ assessment of surprise.

<table>
<thead>
<tr>
<th>Timing/Scenario</th>
<th>$t_0$</th>
<th>$t_{0+1s}$</th>
<th>$t_{0+2s}$</th>
<th>$t_{0+3s}$</th>
<th>$t_{0+4s}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anticipated: Right turn – crossing</td>
<td></td>
<td>1.89</td>
<td>-0.25</td>
<td>0.57</td>
<td>0.44</td>
</tr>
<tr>
<td>cyclist at traffic light</td>
<td></td>
<td>6</td>
<td>15</td>
<td>18</td>
<td>19</td>
</tr>
<tr>
<td>Unexpected: Pedestrian enters the</td>
<td></td>
<td>-0.65</td>
<td>1.56</td>
<td>3.08</td>
<td>3.99</td>
</tr>
<tr>
<td>road between parked cars</td>
<td></td>
<td>11</td>
<td>19</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>Unexpected: Pedestrian enters the</td>
<td></td>
<td>11</td>
<td>19</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>road between parked cars</td>
<td></td>
<td>.527</td>
<td>.135</td>
<td>.006</td>
<td>.001</td>
</tr>
<tr>
<td>Surprising: Turning vehicle takes</td>
<td></td>
<td>-0.94</td>
<td>5.02</td>
<td>6.25</td>
<td>6.48</td>
</tr>
<tr>
<td>right of way</td>
<td></td>
<td>19</td>
<td>18</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>Surprising: Turning vehicle takes</td>
<td></td>
<td>.357</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>right of way</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 3. Reported surprise during the encountered situations. Illustrated are mean values.

If advisory warnings were provided, the participants’ assessments regarding the situation criticality confirmed, as expected, the predictability of the respective conflict (see Figure 3). While the majority of participants rated the anticipated situation as ‘harmless’, the unexpected situation was mainly considered as ‘unpleasant’, and the surprising situation was assessed as ‘dangerous’. This was in accordance with the minimum Time-to-arrival (TTA_{min}) to the respective conflicting road user (see Figure 3), whereby the surprising situation resulted in the shortest TTA_{min}, followed by the unexpected and anticipated situations.

Table 4. T-test for dependent samples statistics, difference to baseline in participants’ assessment of criticality.

<table>
<thead>
<tr>
<th>Timing/Scenario</th>
<th>t0</th>
<th>t0+1s</th>
<th>t0+2s</th>
<th>t0+3s</th>
<th>t0+4s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anticipated: Right turn – crossing cyclist at traffic light</td>
<td>( t )</td>
<td>2.05</td>
<td>-0.36</td>
<td>0.00</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>df</td>
<td>6</td>
<td>15</td>
<td>18</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>( p )</td>
<td>.086</td>
<td>.728</td>
<td>1.00</td>
<td>.748</td>
</tr>
<tr>
<td>Unexpected: Pedestrian enters the road between parked cars</td>
<td>( t )</td>
<td>-1.70</td>
<td>0.35</td>
<td>2.26</td>
<td>3.33</td>
</tr>
<tr>
<td></td>
<td>df</td>
<td>11</td>
<td>19</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>( p )</td>
<td>.118</td>
<td>.728</td>
<td>.036</td>
<td>.004</td>
</tr>
<tr>
<td>Surprising: Turning vehicle takes right of way</td>
<td>( t )</td>
<td>-0.68</td>
<td>5.08</td>
<td>6.43</td>
<td>6.43</td>
</tr>
<tr>
<td></td>
<td>df</td>
<td>19</td>
<td>18</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>( p )</td>
<td>.504</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
</tr>
</tbody>
</table>

Depending on the predictability of the conflict, the presentation of advisory warnings affected subjective and objective situation criticality (see Figure 3; subjective assessment: scenario: \( F = 35.46, p < .001 \); timing: \( F = 16.17, p < .001 \);

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2 (Based on the limited number of only 3 drivers that actually received driver support (see Table 2), the results for the anticipated situation of time t0 were not incorporated into the assessment.)
interaction: $F = 5.16, p < .001$; $\text{TTA}_{\text{min}}$; scenario: $F = 6.16, p = .003$; timing: $F = 46.19, p < .001$; interaction: $F = 10.45, p < .001$). In the anticipated situation, there were neither subjective nor objective changes when using driver assistance. Whether advisory warnings were provided or not, only harmless situations or an average $\text{TTA}_{\text{min}}$ of ≥ 2 seconds were the result. In the unexpected scenario, a decrease of subjective criticality occurred starting with $t_{0+2s}$, and a decrease in objective criticality with $t_{0+1s}$ (see Table 4 and 5).

**Table 5.** $T$-test for dependent samples statistics, difference to baseline in minimum Time-to-arrival.

<table>
<thead>
<tr>
<th>Timing/Scenario</th>
<th>$t_0$</th>
<th>$t_{0+1s}$</th>
<th>$t_{0+2s}$</th>
<th>$t_{0+3s}$</th>
<th>$t_{0+4s}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anticipated: Right turn – crossing cyclist at traffic light</td>
<td>0.15</td>
<td>-0.60</td>
<td>2.18</td>
<td>1.68</td>
<td></td>
</tr>
<tr>
<td>Unexpected: Pedestrian enters the road between parked cars</td>
<td>1.82</td>
<td>-2.18</td>
<td>-4.38</td>
<td>-3.06</td>
<td>-4.04</td>
</tr>
<tr>
<td>Surprising: Turning vehicle takes right of way</td>
<td>2.22</td>
<td>-1.99</td>
<td>-5.89</td>
<td>-4.77</td>
<td>-6.09</td>
</tr>
</tbody>
</table>

Figure 3. Reported situation criticality (left) and $\text{TTA}_{\text{min}}$ to the conflicting road user (right); illustrated are mean values and 95% confidence intervals. If drivers decelerated below a threshold of 5km/h before the conflicting road user entered the conflict area, the resulting $\text{TTA}_{\text{min}}$-values were not reported because they produced large outliers in the data set.
Compared to non-assisted driving during surprising scenarios, the decrease in subjective criticality occurred starting from $t_{0+1s}$, and with objective criticality at $t_{0+2s}$ (see also Table 4 and 5). At this point, it must be stated that, when compared to non-assisted driving, drivers reported a higher criticality if the advisory warnings were provided at $t_0$. Similarly, objective data during these drives indicated lower $TTA_{max}$ values than those drives without assistance. However, this applied to the unexpected as well as the surprising situation.

If advisory warnings were provided only at $t_0$, those messages were evaluated on average as being of little help or falling within the medium range of being helpful (see Figure 4). If advisory warnings were provided earlier, the assessment of these warnings’ usefulness also increased independently from the driving scenario (scenario: $F = 2.51, p = .094$; timing: $F = 6.60, p < .001$; interaction: $F = 0.35, p = .929$). This reflects the reported mitigation of situations if information about upcoming conflicts was received prior to the last possible warning moment; however, this did not hold true if data were received at the last possible moment. With respect to the timeliness with which the advisory warnings were provided, all situations indicate that advisory warnings presented two to three seconds prior to the last possible warning moment ($t_{0+2s}$ or $t_{0+3s}$), received the best assessment (see Figure 4; scenario: $F = 0.48, p = .623$; timing: $F = 69.95, p < .001$; interaction: $F = 0.31, p = .947$).

**Figure 4.** Reported usefulness (left) and timeliness (right) of the advisory warnings; illustrated are mean values and 95% confidence intervals.
Discussion

The effectiveness of early advisory warnings based on cooperative perception in different conflict situations was investigated. The objective of the study was to localize the time frame for such early driver assistance under consideration of the effects related to situational driver expectations. In particular, a positive effect of the driver information could be illustrated in surprising and unexpected situations. In anticipated situations, the driver directs his/her attention autonomously on the conflict situation and, accordingly, does not benefit from such advisory warnings. When advisory warnings were provided, the strongest effect was found when surprising situations occurred. Furthermore, the study results provide data for an optimized advisory warning time frame. Advisory warnings must not be provided as early as possible. On the contrary, information about upcoming conflicts must be provided at least one second prior to the last possible warning moment, better still, two seconds beforehand, in order to have a positive effect on driving behaviour and the associated criticality of the situation. Data supplied even earlier to the driver do not contribute to the mitigation of the situation. Participants consistently preferred, independent from the investigated scenarios, to receive the advisory warnings two to three seconds prior to the last possible warning moment, rather than receiving information on imminent conflict situations. However, at this point it must be emphasized that the determined time frame for advisory warnings applies to the prototype implemented driver-vehicle interface. That is to say, it refers to discrete visual-auditory advisory warnings provided as a visual display element in the simulated HUD accompanied by an acoustic signal. It can be assumed that a more intensive signal, as usually applied during imminent crash warnings, will have an effect at a later point in time.

With regard to the acceptance of advisory warnings, it can be stated that such data are generally perceived by drivers as useful, provided the data are not presented at t₀. The usefulness of early advisory warnings (prior to the last possible warning moment) is consistently assessed as medium to high. Furthermore, the information received during scenarios that were still safely managed by the driver without assistance is considered helpful on average. The results emphasize that the information system for the avoidance of traffic conflicts, as it was implemented prototypically in this study, are generally perceived as useful by the drivers. However, the subjective assessment of the usefulness does not reflect in all cases an objective benefit in driving behaviour.

The increase in situation criticality for advisory warnings provided at t₀ during unexpected and surprising scenarios must be seen as a potentially problematic issue. Mathematically, from the moment of receiving the information, the driver has one second to start the activation of the brakes. Nonetheless, compared to non-assisted driving, lower TTA_{min}-values can be found in these scenarios. The following offers possible explanations: (1) adaptation of the brake reaction to the information system (in most assisted scenarios more reaction time is available), (2) an increase in speed during assisted driving compared to non-assisted driving, or (3) a distraction effect caused by reading the visual display element and thus requiring more response time.
A clarification of this effect was not possible within the scope of this study; however, subsequent studies are anticipated.

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