Graded auditory feedback based on headway: An on-road pilot study

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Abstract

Auditory feedback produced by driver assistance systems can benefit safety. However, auditory feedback is often regarded as annoying, which may result in disuse of the system. An auditory headway feedback system was designed with the aim to improve user acceptance and driving safety. The algorithm used a graded approach, which means that it delivered a more urgent warning if the time headway was smaller. In an on-road test, we compared this design with a conventional binary headway warning system. Participants drove a test vehicle on the highway, once with our graded feedback and once with conventional feedback. User acceptance was assessed through a questionnaire and interview. An inspection of the time headway distributions suggested that participants responded to the auditory feedback for both systems. There were substantial individual differences in time headway, and extremely short headways were rare. These findings suggest that long-term naturalistic trials are needed to assess the safety-effectiveness of graded auditory feedback.

Introduction

Car driving is safer than ever before (Stipdonk, 2017). The growing number of advanced driver assistance systems (ADAS), such as forward collision warning systems (FCW), may contribute to a further reduction of accidents. Auditory feedback is an attractive modality for in-vehicle warning systems because auditory feedback interferes little with the visually demanding driving task and can convey informative messages with different levels of urgency (Bazilinskyy & De Winter, 2015; Stanton & Edworthy, 1999).

ADAS often employ auditory feedback. Typically, the momentary safety margin (e.g., time to collision [TTC] or time headway [THW]) is used as an index to determine when feedback should be provided to the driver. A disadvantage of such discrete auditory warnings is that they may annoy the driver due to their saliency, repetitiveness, or binary nature without a clear indication of the reason for issuing feedback (Gonzalez et al., 2012; Parasuraman et al., 1997).

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There is a balance between delivering feedback and maintaining user acceptance: if the decision threshold (criterion) is set so that auditory warnings are provided late, the warnings may be ineffective because the driver is caught by surprise or has little time to respond. Conversely, if the decision threshold is set so that warnings are provided early, the driver may become annoyed by the frequent warnings, and he/she may ignore or disable the warning system (Parasuraman & Riley, 1997). According to Sarter (2005), graded notifications, defined as “notifications that consist of signals that are proportional to the degree of urgency” are a promising yet underutilized means of supporting operators. Indeed, auditory warnings are sometimes not well-accepted (Parasuraman & Riley, 1997; Parasuraman et al., 1997; Wiese & Lee, 2004).

Several approaches exist to improve the acceptance of warning systems. One strategy is to provide individualization through adaptable or adaptive settings based on the driver’s behaviour and driving style (e.g., Wang et al., 2013). Although this may improve acceptance, varying thresholds may also be a source of confusion for the driver. Providing the driver with information about why the warning is given, or providing clues that allow the driver to resolve the situation before the warning is triggered may also benefit acceptance.

The Dutch Institute for Road Safety Research (SWOV) sees any headway under 2.0 s as unsafe (SWOV, 2012), whereas the National Highway Traffic Safety Administration (NHTSA) reports that headways under 1.2 s are unsafe (NHTSA, 2004). In practice, however, drivers may adopt considerably shorter headways: highway observations showed that many drivers adopt a THW below 1 s (Hoogendoorn & Botma, 1997; Brackstone & McDonald, 2007; Treiber et al., 2006). An increase of minimal headway may improve safety (Ohta, 1993; Saffarian et al., 2017), whereas a reduction of variance of headway stabilizes traffic flow on the highway (Xie et al., 2008; Ye & Zhang, 2009).

In this study, we designed a new type of auditory feedback system and compared it to a conventional system. We propose auditory feedback that becomes more urgent (and therefore having a higher potential for annoyance) when the level of risk (operationalized in terms of three THW stages) is higher. An on-road measurement was conducted to pilot-test whether the system worked as it should, and how drivers responded to it.

Methods

Auditory feedback design: Survey study

As a first step to develop a feedback system based on headway, we performed an online survey among the student community and family members (N = 69). This survey compared user preferences for different types of earcons informing about the time headway. The sample consisted of 50 males and 18 females (one person preferred not to specify their gender). They had a mean age of 26.2 years (SD = 11.8).

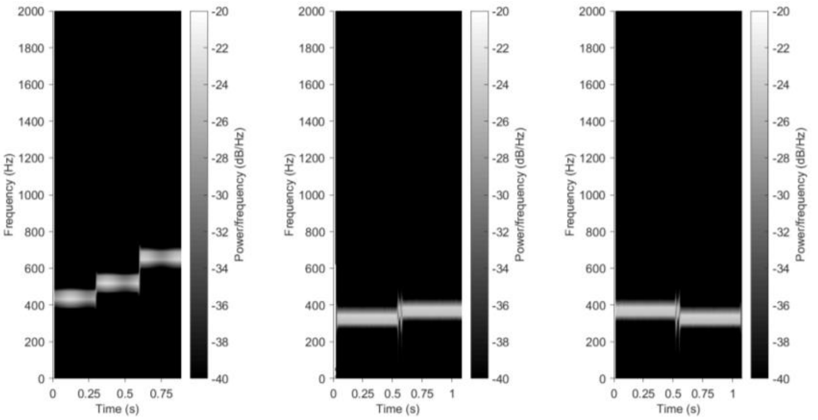

Figure 1. Spectrograms of Earcon 1 (left), Earcon 2 (centre), and Earcon 3 (right) from the online survey.

The respondents were asked to select the most suitable earcons for warning that the distance to lead vehicle is too short. They did this by ranking three selected earcons according to their preference. The earcons consisted of melodies that were assumed to be non-annoying. Figure 1 shows the spectrograms of the three sounds. The sounds were provided in three short clips (Figure 2). Each clip showed the same dash camera clip in which the driver was approaching another car. All earcons stood out from the highway traffic noise. The first earcon (Earcon 1) was a 900 ms three-note climbing tune (440 Hz, 523 Hz, 659 Hz), each note lasting 300 ms. The second and third earcons consisted of a two-note melody (330 Hz, 370 Hz), both tones lasting 500 ms. In Earcon 2 the lower frequency tone was presented first, followed by the higher frequency tone. In Earcon 3, the higher frequency tone was presented first, followed by the lower frequency tone. The earcon was provided when the THW in the video was approximately 0.5 s.

Figure 2. Video used in the online survey to study preferences for types of earcons informing about the headway (headway about 0.5 s).

The results are shown in Table 1. 68.1% of the respondents selected Earcon 1 as their first preference. Choices of the participants were assigned with ratings, where the first choice received 3 points, the second choice 2 points, and the third choice 1 point. The earcon with the highest rating (i.e., Earcon 1) was selected for use in the on-road study.

Table 1. Left: Reported orders for offered earcons. Right: rating of the earcons, where the first choice gets 3 points, second choice 2 points, and third choice 1 point.

Order or preference	*Percentage*
Earcon 1 – Earcon 2 – Earcon 3	44.9%
Earcon 1 – Earcon 3 – Earcon 2	23.2%
Earcon 2 – Earcon 3 – Earcon 1	14.5%
Earcon 2 – Earcon 1 – Earcon 3	5.8%
Earcon 3 – Earcon 1 – Earcon 2	5.8%
Earcon 3 – Earcon 2 – Earcon 1	5.8%

Earcon	*Rating*
Earcon 1	171
Earcon 2	132
Earcon 3	111

A question on the preferred headway at which to receive warnings was also asked. Participants were asked to rank the headways at which the cautionary warning should be given. Again, three videos were provided (same video as with Earcons 1–3), in which a neutral beep was played at three different THWs in this order: 0.5 s, 0.8 s, and 1.2 s. As above, choices of the participants were assigned with ratings, where the first choice received 3 points, the second choice 2 points, and the third choice 1 point. The results are shown in Table 2. The most preferred option was Timing 1 (0.5 s). Timing 2 (0.8 s) was almost as popular as Timing 1 (157 and 175 points, respectively). Timing 3 (1.2 s) was the least popular (82 points). In summary, the results suggest that feedback that is provided early is not preferred by participants.

Table 2. Left: preferred orders for headway timings. Right: rating of the earcons, where the first choice gets 3 points, second choice 2 points, and third choice 1 point.

Order or preference	*Percentage*
Timing 1 – Timing 2 – Timing 3	59.4%
Timing 1 – Timing 3 – Timing 2	2.9%
Timing 2 – Timing 3 – Timing 1	4.3%
Timing 2 – Timing 1 – Timing 3	27.5%
Timing 3 – Timing 1 – Timing 2	1.4%
Timing 3 – Timing 2 – Timing 1	4.3%

Timing	*Rating*
Timing 1	175
Timing 2	157
Timing 3	82

Conventional auditory feedback on headway

A Conventional feedback system was implemented. It produced an urgent sound (hereafter referred to as ‘Sound 2’) if the THW was smaller than 0.6 s. This sound was the same as Earcon 1 from the online survey, but the timbre was a square wave instead of a sine wave to convey a stronger sense of urgency.

Graded auditory feedback design

The above findings were used in the design of a 3-stage headway alerting system. A cautionary warning (Sound 1, identical to Earcon 1 from the online survey) was given the first time the THW dropped below 0.8 s. After this, between 0.8 s and 0.5 s (Stage 1), the informative message “Following distance too short” (Voice 1) in Dutch was played every 8 s. Based on recommendations from a previous survey on auditory in-vehicle interfaces (Bazilinskyy & De Winter, 2015) and an online experiment on the qualities of voice-based displays for cars (Bazilinskyy & De Winter, 2017), a computer-generated female voice was used for the voice-based warning. The 8 s timer was reset when the THW became larger than 1.0 s.

If the THW dropped below 0.5 s, another cautionary warning was provided once (Sound 2). As pointed out above, Sound 2 was identical to Sound 1, but had a more urgent sounding timbre. Between 0.5 and 0.3 s (Stage 2), an urgent voice (Voice 2) told the driver every 5 s in Dutch with Belgian accent to “Increase headway”.

If the THW was shorter than 0.3 s (Stage 3), an imminent 659 Hz 300 ms alarm (Sound 3) was issued every 0.7 s until the THW increased. Figure 3 shows the spectrograms of the three sounds.

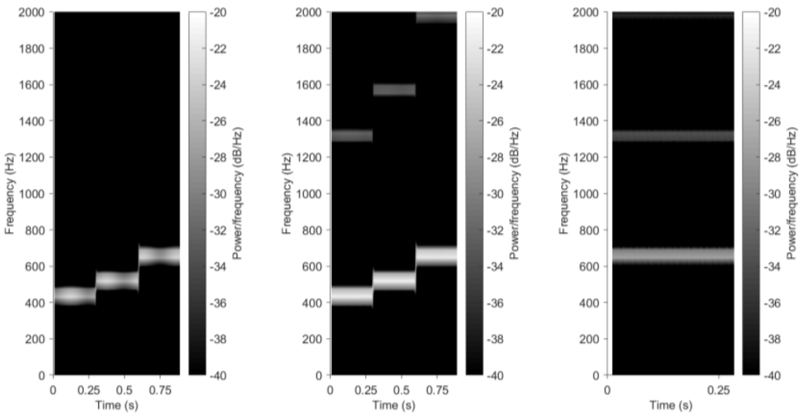

Figure 3. Spectrograms of Sound 1 (left), Sound 2 (centre), and Sound 3 (right) from the Graded auditory feedback.

A suppressing algorithm was implemented to reduce the occurrence of alarms in Stages 1 and 2. This algorithm suppressed all warnings (except in Stage 3) if the filtered THW (moving average over five preceding samples; i.e., 0.5 s of data) was increasing. This suppressing algorithm was implemented in the Graded system only.

Sound feedback was provided only if at the moment of crossing the THW threshold (i.e., ≤ 0.8 s for Stage 1, ≤ 0.5 s for Stage 2, ≤ 0.3 s for Stage 3) the THW was within that threshold at least 0.5 s before. This additional filter suppressed feedback if the threshold was crossed only briefly, causing a maximal time delay of 0.5 s. This additional filter was present in both the Graded system and the Conventional system.

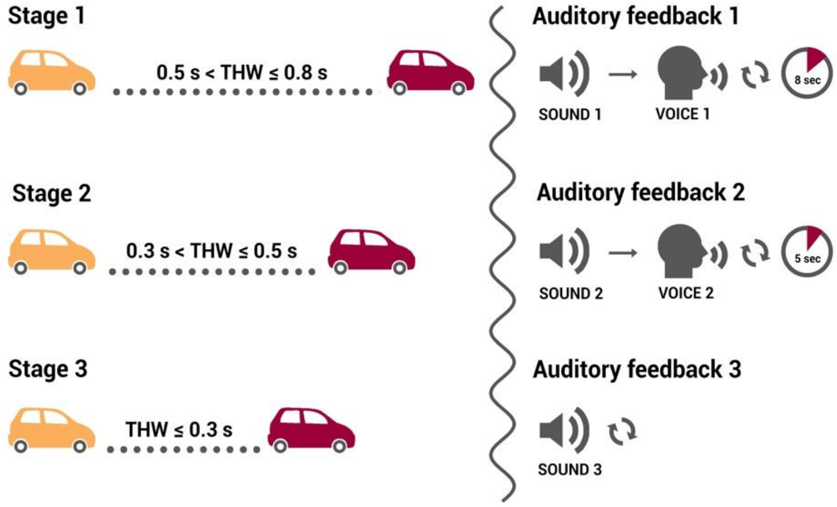

Figure 4. Visualisation of the Graded headway feedback system.

Procedures of the on-road experiment

The auditory feedback was implemented in Python and installed on a Raspberry Pi computer in a Volvo C30. Measurements on driving speed, the status of turning lights, the position of gas and brake pedals, steering angle, THW were obtained through a Mobileye system. All sounds were played through the JBL GO loudspeaker. The leading car was a Nissan Micra.

Twenty people participated in the experiment over the course of three days. The sample consisted of 13 males and 7 females. They had a mean age of 20.5 years (*SD* = 1.6). Five participants indicated to have driven less than 1,000 km in the past 12 months, 12 participants reported 1,001–5,000 km, and 3 participants reported 5,001–15,000 km. Participants provided written informed consent and were informed that the study involved auditory feedback, that the feedback is not necessarily perfect, and that they should remain attentive to the road. Participants were further asked to drive as they normally would. The participants then took place in the test vehicle together with two observers.

The participants drove a total of 14 km on a Dutch highway (A13, from the Molengraaffsingel in Delft to the Schieveensedijk in Rotterdam, and back). When this road was congested, a track of similar length was driven on the A4 or N470. The driver was not informed about the route but was instructed to follow a car, driven with a normal driving style by one of the authors. Each drive took approximately 15 minutes and was divided into two parts of equal length. Half of the participants started with the Conventional system enabled, and the other half started with the Graded feedback system enabled. Halfway, the feedback system was changed from the Graded feedback system to the Conventional system, or vice versa. The driver was notified of the system change. When the car had returned to its starting location, the driver was asked to complete a questionnaire to measure acceptance of both systems (Van der Laan et al., 1997). The acceptance questionnaire measured two variables, namely the satisfaction and the usefulness of the systems. The participants were also interviewed on how they had experienced the two systems. It consisted of open questions that first identified which differences the participant had noticed between the two systems, and then asked their opinion regarding the used warnings and their timing.

Results

During the experiment, 11 out of the 20 participants (9 males, 2 females, mean age = 20.9, *SD* age = 1.5) drove with a headway close enough to receive feedback from both systems (i.e., at least once in each of the two drives). Only the results of these 11 participants will be considered here. The average time that participants drove faster than 50 km/h was 294 s (*SD* = 123 s, min = 159 s, max = 586 s) for the Conventional system and 286 s (*SD* = 141 s, min = 208 s, max = 682 s) for the Graded system.

Table 3 provides an overview of the number of times that feedback was provided per condition, for the 11 participants combined. It can be seen that the full potential of the Graded feedback system was not tested. That is, participants rarely drove close to the lead vehicle, and therefore Voice 2 was uttered only three times. Sound 3 was provided only once, possibly because of a misdetection or another vehicle cutting in.

Further analysis showed that while driving speed exceeded 50 km/h, the filter of the Graded system suppressed Sound 1 on 7 occasions, Voice 1 on 8 occasions, Sound 2 on 11 occasions and Voice 2 on 3 occasions. In other words, the filter appeared to be effective in *not* providing feedback when the driver was already responding.

Table 3. Number of times that a particular feedback was provided.

	Conventional system	*Graded system*
Sound 1	0 times	52 times
Voice 1	0 times	20 times
Sound 2	49 times	11 times
Voice 2	0 times	3 times
Sound 3	0 times	1 time

Note. The working mechanism of the Graded system is illustrated in Figure 2. The Conventional system provided feedback at a THW of 0.6 s. Only driving speeds greater than 50 km/h were considered.

Figure 5 shows a distribution of the recorded THW for both systems. These results tentatively indicate that the systems affected THW, as THWs higher than 0.6 s were relatively prevalent for the Conventional system whereas THWs higher than 0.8 s were relatively prevalent for the Graded System. In other words, the THW distribution is consistent with the fact that the Conventional system provided feedback at a THW of 0.6 s, whereas the Graded System gave its first beep at a THW of 0.8 s. We refrained from statistical testing due to the relatively small sample size. One issue that we observed was that there were large individual differences in following distance (Figure 6), where some participants received considerably more feedback than others.

Self-reported acceptance

Figure 7 shows the results of the acceptance questionnaire. The magenta markers represent the two systems that were tested herein. The other markers correspond to previous experiments in which participants were provided with a warning (take-over request) indicating that they had to take over control from automated driving (Bazilinskyy et al., 2017). Both the Conventional and Graded Systems received mediocre ratings on the scale from −2 to 2.

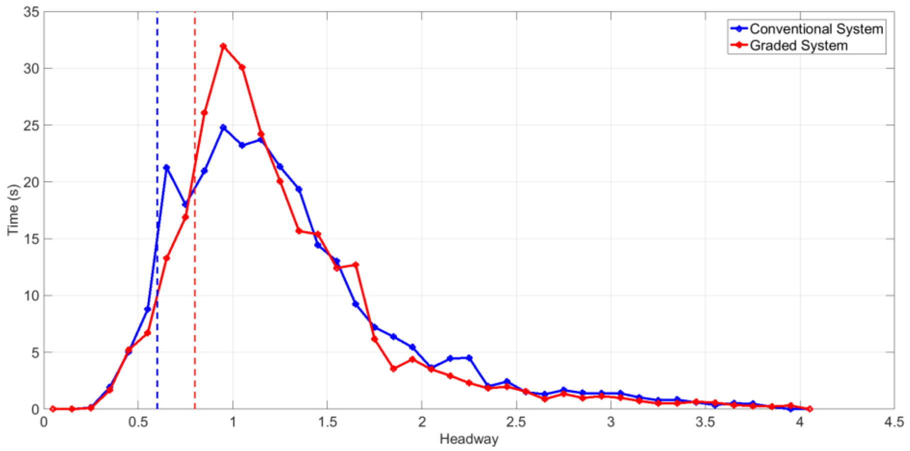

Figure 5. Distribution of time headway (THW). Time headway is defined as the distance headway divided by the own vehicle's speed. A distribution was calculated per participant and then averaged over the 11 participants. Only driving speeds above 50 km/h were considered. The vertical blue and dashed red lines represent the threshold for providing the first feedback in the Conventional and the Graded system, respectively.

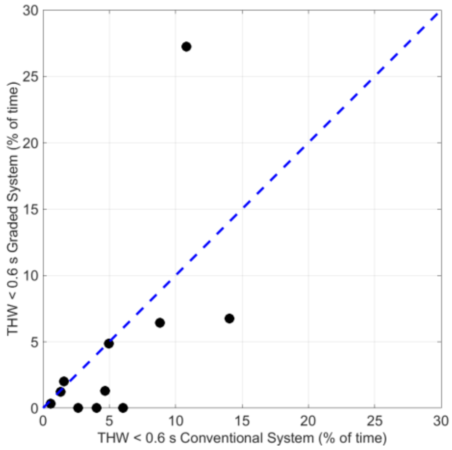

Figure 6. Percentage of time that participants drove at a time headway (THW) smaller than 0.6 s. Only driving speeds above 50 km/h were considered. It can be seen that there were substantial individual differences.

Interviews

The participants were asked questions about how they experienced the two systems, and about their attitude towards the occurrence and selection of sounds. Seven (out of eleven) participants preferred the Graded system over the Conventional system, two preferred the Conventional system, and two accepted neither system. Five participants reported they would like to receive feedback at a shorter THW for the Graded system and one driver would have preferred a shorter THW for the Conventional system. Four participants mentioned that they had experienced a delay in the feedback of the Graded system and regarded this as a negative aspect. Two participants reported trouble in understanding the spoken voice, and one participant reported a negative attitude towards the use of voice for headway warning systems.

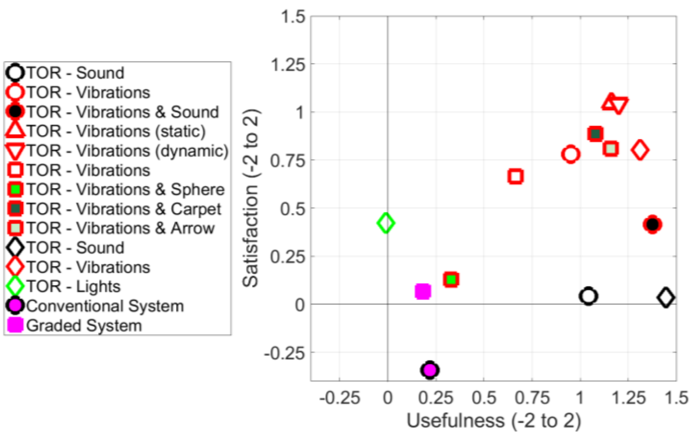

Figure 7. Self-reported usefulness and satisfaction of the tested systems (magenta square and circle) in comparison to previous auditory, visual, and vibrotactile warnings tested in driving simulators. TOR = Take-over request.

Discussion

We designed an auditory feedback system that provided feedback based on THW stage and time spent in a stage (Figure 4). A filter was added to ensure that no feedback was provided when the headway was already increasing. We expected that our design would yield better acceptance than a conventional system that provided binary feedback when a single THW threshold was exceeded.

Our algorithm was pilot-tested on a public road. Results suggest that participants, on average, did respond to the feedback, as shown from the THW distribution (Figure 5). However, we also found that the experimental design was not suitable to properly test the system as participants hardly entered the more dangerous stages. Long-lasting naturalistic driving tests are needed to examine the effect on the THW distribution and the occurrence of hazardous situations (e.g., low time to collision values) (cf. Shinar & Schechtman, 2002). In particular, the topic of individual differences deserves further examination. Some participants may hardly ever receive feedback, whereas others tend to drive at short headways for a significant portion of their driving time.

The filter reduced the number of warnings in the Graded system, especially those following a lane change. However, the interviews revealed that some drivers perceived 'delayed feedback' of this system. This delay may have been caused by the filter, which suppresses warnings after a cut-in by another vehicle if the headway already increases, but can trigger a late warning if the headway stops increasing while the THW is still small. The benefits of fewer warnings may, therefore, have caused a reduction in predictability.

The results showed that self-reported acceptance was relatively low as compared to previously tested systems that warn drivers about an impending collision in a driving simulator (Figure 7). It is possible that drivers accept systems that warn them of an imminent threat, but they may be less accepting towards warnings while they are already alert in a regular car following task (as in the present study). Furthermore, it is possible that drivers may be more accepting towards visual or vibrotactile feedback than to auditory feedback, or that simulator-based research yields higher acceptance ratings than on-road research. Future research could be directed towards more refined algorithms that minimize the likelihood of nuisance alarms while retaining a high acceptance.

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