Blind Driving by Means of a Steering-Based Predictor Algorithm

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Abstract. The aim of this work was to develop and empirically test different algorithms of a lane-keeping assistance system that supports drivers by means of a tone when the car is about to deviate from its lane. These auditory assistance systems were tested in a driving simulator with its screens shut down, so that the participants used auditory feedback only. Five participants drove with a previously published algorithm that predicted the future position of the car based on the current velocity vector, and three new algorithms that predicted the future position based on the momentary speed and steering angle. Results of a total of 5 h of driving across participants showed that, with extensive practice and knowledge of the system, it is possible to drive on a track with sharp curves for 5 min without leaving the road. Future research should aim to improve the intuitiveness of the auditory feedback.

Keywords: Road safety · Driver support · Auditory display · Human–machine interface · Driving simulator

1 Introduction

Road traffic crashes are a major public health problem. If no action is undertaken, road crashes will become the seventh leading cause of death by 2030 [1]. About 95% of crashes are caused by driver error, in particular inattention and distraction [2].

One way to avoid crashes caused by poor driver behavior is automated driving [3]. An important technology, which may be seen as one of the first steps towards autonomous driving, is automated lane keeping—as used in modern Tesla and Mercedes Benz cars, for example. Current automated driving systems cannot predict the behavior of other road users in all situations. Once the system fails to handle a traffic situation, the driver needs to take over the steering and keep the car on the road. These transitory situations are a safety concern if the driver fails to reclaim control properly. The median estimate among the general public is that autonomous driving will be widespread by 2030 [4], whereas some experts argue that autonomous driving will not be feasible before 2075 [5]. Until driving is autonomous, automated driving systems will require driver intervention at certain times.

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The aim of this research was to develop and perform a preliminary evaluation of a lane-keeping assistance system in which drivers are supported by auditory feedback as a function of the position on the road [6]. Auditory feedback may be beneficial for regaining steering control from automated driving, especially if the driver is visually overloaded. Auditory feedback may also be useful in regular manual driving when visual information is temporarily lacking, such as when driving in heavy fog or during a visual distraction.

Previous research concurs that the use of real-time feedback can enhance driving performance. Such performance gains were demonstrated for example by Powell et al. [7], who provided tonal cues to racing drivers based on the lateral G-force, and by Houtenbos et al. [8], who provided auditory beeps as a function of the speed and direction of another car approaching an intersection. Furthermore, lane departure and forward collision warning systems are already commercially available. In these systems, the driver is alerted by audio when a problem occurs.

We tested auditory feedback concepts while drivers did not receive any visual information regarding the road environment. This 'blind driving' paradigm can be regarded as the ultimate condition for testing human-machine interfaces: if drivers are able to steer a vehicle by means of sound only, this may provide evidence that the sound cues are effective if visual information is compromised.

This paper presents a design iteration of a previous concept of blind driving by means of auditory feedback (hereafter called 'Blind Driving 1'; BD1 [9]). The focus in BD1 was on investigating how far into the future the system has to 'look' to determine the predicted position of the car—the prediction time. In BD1, auditory feedback was based on the predicted location of the car 0 s, 1 s, 2 s or 3 s into the future. When the predicted location of the car deviated more than 0.5 m from the center of the lane, audio feedback (i.e., a tone) was issued to alert the drive to correct their trajectory. The tone became louder the farther the predicted position was from the lane center. Results of this previous project showed that without predictor feedback (i.e., 0 s prediction), participants were more likely to depart the road compared to with predictor feedback. In this paper, the algorithm presented in BD1 is enhanced with the aim to improve the accuracy of the prediction path.

2 Method

2.1 Apparatus

A fixed-base driving simulator was used (Fig. 1; Green Dino, The Netherlands). An interface was programmed in MATLAB/Simulink r2015a to retrieve location, speed, and steering data from the simulator and to generate audio output via Sennheiser CX-200 headphones. When wearing the headphones, the participants were still able to hear engine and tire sounds via loudspeakers mounted in the simulator. Similar to BD1, the participants had to steer away from the sound: sound on the left was produced when the predicted lateral error was left of the center of the right lane, and vice versa. During the experiment, the screens of the simulator were turned off.

Fig. 1. The driving simulator used in this research. In all trials, the screens were turned off and participants wore headphones.

2.2 Track

The track was a two-lane 7.5-km road without intersections and without other road users (Fig. 2). It contained straight segments and mostly 90-degree sharp curves with a radius of about 20 m (for research using the same track, see [9–12]). The lane width was 5 m. The width of the simulated car was 1.76 m, and its length was 4.22 m. In each trial, participants drove 5 min. The driven distance per trial varied between 2,069 m and 4,206 m, depending on the number of times the car left the road and was reset on the center of the right lane with zero speed. If driving the full 4,206 m, participants encountered twelve 90-degree curves and one 180-degree curve.

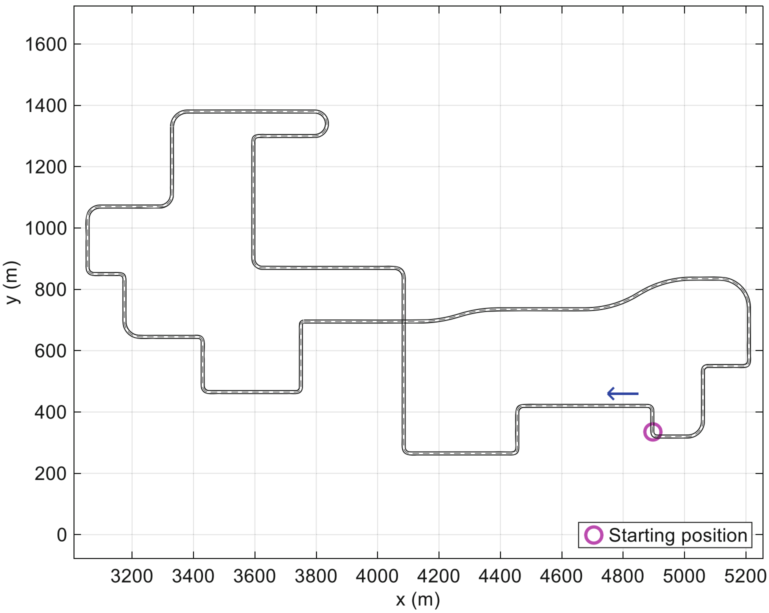

Fig. 2. The test track.

2.3 Participants

In total, five males (mean age = 26.6 years, SD = 6.3 years) participated in the study. None of the participants had hearing impairments. Participants 1–4 (authors 2–5 of this paper) had been involved in the design, and therefore had detailed knowledge of the feedback concepts. Participant 5 was an expert racing driver who was new to the feedback designs and was not informed about their working mechanisms in any way. Participant 5 was invited in order to investigate how well a competent driver, who is naïve to the auditory systems, is able to keep the car on the road.

2.4 Speed and Gearbox Settings

An automatic gearbox was used. The speed of the car was predetermined; the participants did not use the pedals. The car automatically accelerated to a speed of about around 80 km/h on straights, and decelerated to 20–40 km/h for the curves, depending on curve radius.

2.5 New Algorithm for Issuing Feedback

In the BD1 concept, when driving through a curve, the predicted location of the car was mostly outside of the road boundaries because the prediction was based on the momentary velocity vector of the car. In the present study, the steering angle was used in the prediction, making it possible to create a more accurate prediction of the future position of the car (see also [13, 14]). Figure 3 illustrates the predicted path in the BD1 and BD2 algorithms, both for a 2 s prediction.

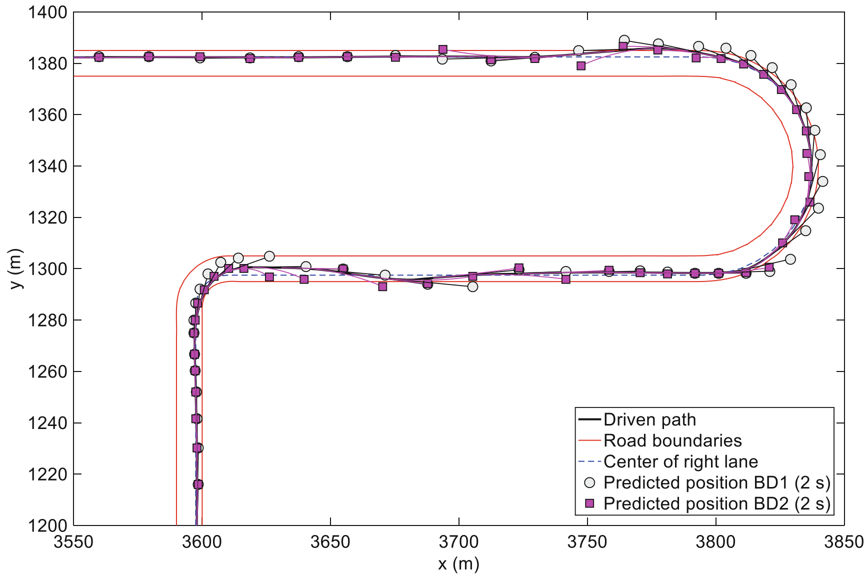

Fig. 3. Working mechanism of the BD1 versus BD2 predictor feedback, both with a 2 s prediction. The figure shows the path driven by a participant through two curves. The circular markers represent the predicted position with the BD1 system (a straight line from the current location), whereas the square markers represent the predicted position with the BD2 system (a curved path from the current location). The markers are shown with 1 s intervals.

It was observed in preliminary tests that a shorter prediction time yielded better driving performance at high speeds and on straights, whereas a longer prediction time yielded better driving at lower speeds and in curves. Long prediction time on straights may lead to oscillatory steering behavior, because a small error is amplified by a long prediction path. A variable prediction time may solve these problems. This study included a condition with a prediction time that varied, from 3 s at 20 km/h (in curves) to 2 s at 80 km/h (on straights).

An overview of the tested concepts is provided in Table 1. In summary, there were two different kinds of feedback: feedback from iteration 1 (BD1), which linearly predicts the vehicle location, and feedback based on the algorithm presented in the current iteration (BD2), which takes steering into account.

In all concepts, volume feedback was provided when the predicted lateral position with respect to the center of the right lane exceeded 0.5 m. The larger the distance from the lane center, the louder the volume became. Further details about the pitch and volume are provided in [9]. The decision to select a 1 m wide tolerance zone was based on our earlier research in which the same threshold was used [9, 15]. De Groot et al. [15] also indicated that off-target feedback (i.e., augmented feedback provided when deviating more than 0.5 m from the lane center) yielded better lane keeping performance than on-target feedback (i.e., augmented feedback provided when deviating less than 0.5 from the lane center).

Table 1. The four blind driving concepts that were tested by the five participants.

Feedback name	Prediction type
BD1 (2 s)	2 s prediction based on current car speed
BD2 (2 s)	2 s prediction based on current car speed and current steering angle
BD2 (3 s)	3 s prediction based on current car speed and current steering angle
BD2 (3 s)	Variable 2–3 s prediction (3 s when driving at 20 km/h, 2 s when driving at 80 km/h) based on current car speed and steering angle

2.6 Experiment Design

Participants 1–4 tested each of the four algorithms three times, in counterbalanced order. Participant 5 tested each of the four algorithms two times, and also drove four times with visual information (twice with and twice without the BD2 variable algorithm), in counterbalanced order. In summary, each participant performed a total of 12 trials of 5 min each (i.e., 1 h of driving per participant).

2.7 Dependent Variables

Driving performance was assessed by means of the number of resets. A reset occurred when the car drove outside of the road boundaries with all its four corners. Secondly, the on-target percentage (OTP) was used as a measure of lane-keeping accuracy. OTP was defined as the percentage of time that the current absolute lateral position was less than 0.5 m. Data from 3 s prior to 10 s after each reset were excluded from the calculation of OTP.

3 Results

Figure 4 shows the number of resets that the five participants experienced with the four tested systems. The variable prediction time and the 3 s prediction time led to better performance than the other two algorithms. It is noteworthy that for the BD1 system, Participant 5 performed better than Participants 1–4. Participants 1–4 performed better with the BD2 systems (which they designed themselves) than with the BD1 system.

Most resets occurred around curves (see Fig. 5 for an illustration). The prediction time in curves for the variable model was mostly around 3 s (as there are few curves where the car reaches a speed higher than 20 km/h). This explains that the resets for the 3 s prediction time and variable prediction times are similar (Fig. 4). There was one trial without a single reset, for the BD2 system with a 3 s prediction time.

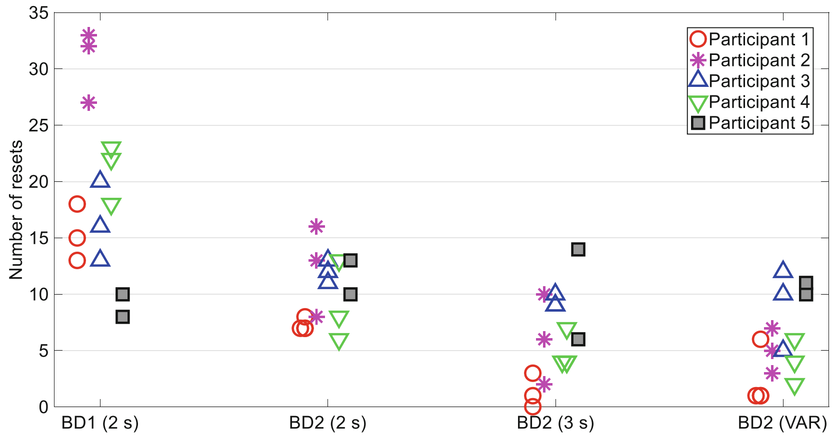

Fig. 4. Number of resets.

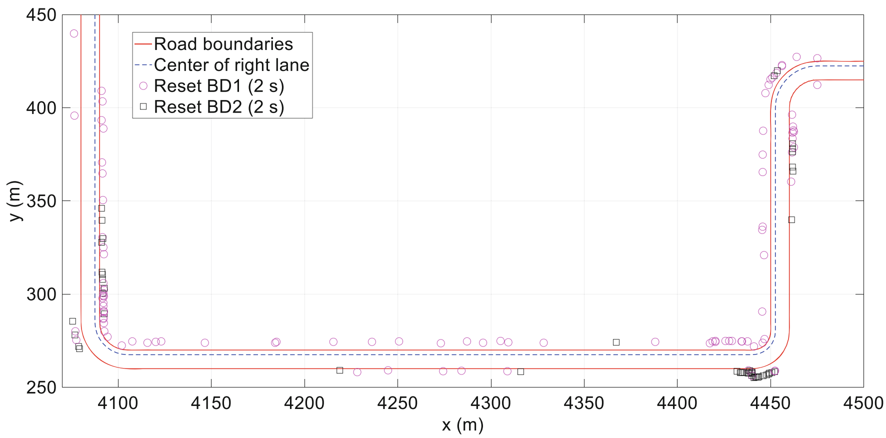

Fig. 5. Locations of resets in part of the course for two of the four algorithms. It can be seen that participants crashed on distinct locations depending on the curve and the concept used.

The results for OTP (Fig. 6) mirror the results of the number of resets (Fig. 4), with the BD1 system yielding lower OTP values than the three BD2 systems, for Participants 1–4. It can also be seen that there were substantial individual differences, with some participants performing substantially better than others. There was no trial that had an OTP greater than 50%. As a reference, Participant 5 attained an OTP of 98% when driving with visual feedback in one of his trials.

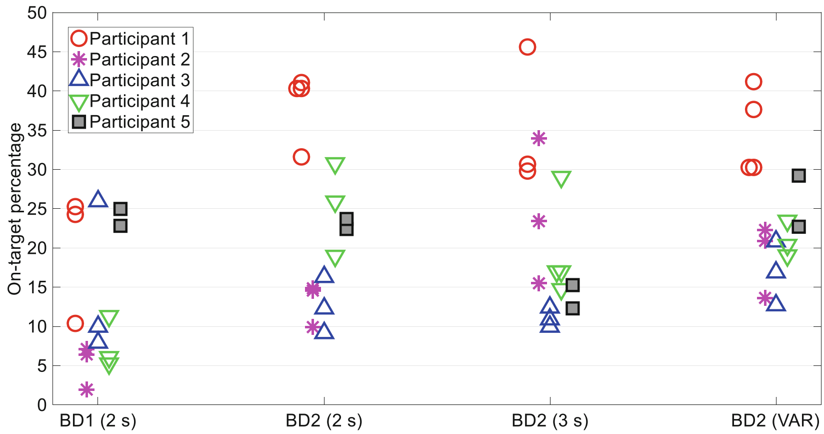

Fig. 6. On-target percentage.

4 Discussion

In this design study, we implemented a predicted position based on momentary steering angle, for providing real-time auditory feedback to the driver.

The results of test drives with human subjects suggest that the proposed concept of using steering angle in the prediction of future position yielded a substantial improvement in driving performance as compared to a velocity-based predictor (Fig. 4), although the proposed concept still yielded resets during driving. The prediction time of 3 s featured one trial without a single reset. In other words, with sufficient practice and knowledge of the workings of the system, it is possible to drive a course for 5 min without leaving the road, purely based on auditory information.

The experiment was conducted with four young male engineering students as participants, who were also working on the project. Hence, these participants are not representative of the general population. Furthermore, because the sample size was small, we did not apply null hypothesis significance testing of any sort. Instead, the goal of this work was to examine whether it is possible to drive blindly by means of sound only.

Participant 5 drove without prior knowledge of the algorithms and performed better with the BD1 algorithm than Participants 1–4 did. Participant 5 commented afterwards that the auditory feedback was very hard to understand even after several trials of practice and after having driven with visual feedback and auditory feedback combined. The fact that the BD1 and BD2 concepts were not based on current lateral position, but on future lateral position, and the fact that BD1 and BD2 required different steering actions for a given audio input, may have been confusing. Participant 5 mentioned afterwards that he had not realized that the way the audio feedback has to be used is fundamentally different for these two algorithms. In BD1, no auditory feedback implies that the driver has to drive straight ahead; therefore, the steering wheel should be in the centered position. In the BD2 algorithms, feedback promotes a change of steering wheel position: no sound means the steering wheel is at the correct angle, and if there is audio feedback, the driver has to keep turning the steering wheel until the sound stops. These findings suggest that future research should be directed towards the intuitiveness and stimulus-response compatibility of the auditory stimuli.

In the future studies we propose to investigate the effectiveness of multimodal feedback (e.g., a combination of vibrotactile and auditory feedback) in blind driving. A more realistic scenario in which participants have to control the speed of the car themselves may also yield insightful insights. Further development of techniques for issuing auditory feedback based on the type of road and type of curve may also be required. Additionally, future research should apply larger sample sizes as well as female participants. Finally, we point out that the idea of blind driving using headphones is not practical for real-life applications. Our experiment should be seen as a paradigm for investigating the value of auditory feedback under conditions where visual feedback is compromised. Future research could investigate spatial auditory feedback (e.g., via the car's speakers) in naturalistic conditions, such as driving when being visually distracted, when driving in rain or fog, or when visual information is otherwise unavailable or occluded.

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