The Effect of Haptic Guidance on Curve Negotiation Behavior of Young, Experienced Drivers

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Abstract—Haptic feedback on the steering wheel is reported in literature as a promising way to support drivers during steering tasks. Haptic support allows drivers to remain in the direct manual control loop, avoiding known human factors issues with automation. This paper proposes haptic guidance based on the concept of shared control, where both the driver and the support system influence the steering wheel torque. The haptic guidance is developed to continuously generate relatively low forces on the steering wheel, requiring the driver’s active steering input to safely negotiate curves. An experiment in a fixed-base driving simulator was conducted, in which 12 young, experienced drivers steered a vehicle—without and with haptic guidance—at a fixed speed along a road with varying curvature. The haptic guidance allowed drivers to slightly but significantly improve safety boundaries in their curve negotiation behavior. Their steering activity was reduced and smoother. The results indicated that continuous haptic guidance is a promising way to support drivers in actively producing (more) optimal steering actions that continuous haptic guidance is a promising way to support drivers during curve negotiation.

Keywords—haptic guidance, haptic feedback, curve negotiation, driving, shared control, simulator experiment

I. INTRODUCTION

In recent years there has been an exponential increase in research on systems that aim to improve driver safety and comfort, often called advanced driver assistance systems (ADAS). These systems can roughly be divided into automation systems and support systems (see [1] for an extensive review of passive and active driver support systems).

Automation systems relieve drivers of continuously executing a control task within automation-dependent boundaries, usually defined by either system or delegated authority limitations. Alerts and warnings are used to inform drivers when the automation’s boundaries are reached. Literature provides ample evidence of human factors issues with automation, for example, complacency, over-reliance, loss of situation awareness or even skills [2]. Several car manufacturers have introduced automation systems on the market for longitudinal control: cruise control that automates speed maintenance; adaptive cruise control that automates cruise following. However, not all tasks are (yet) well-suited to be automated. Many driving situations are difficulty to measure, identify, and/or quantify objectively and the human ability to adequately respond to unpredictable situations is often invaluable.

Support systems may help to inform the driver of impending hazards while still keeping him/her in the direct manual control loop. The three commonly used human modalities in support system design to communicate with drivers are vision, audio, and haptics.

Since many driving tasks already are primarily visual tasks, increasing the visual demand during driving might have adverse effects. For example, [3] report that increased visual demand (due to a visually demanding secondary task) reduced speed and increased lane keeping variation in both driving simulators and instrumented vehicles.

Auditory support is limited in the sense that it is not very suitable for continuous support of a control task. Audio is, however, widely used and effective in attention grabbing through alert and warning sounds and voice messages [4], [5].

For most steering tasks the criticality changes continuously, complicating the use of binary warnings (whether visual, auditory or haptic) due to nuisance and difficult threshold settings. Continuous feedback, as [2] argues, is therefore highly suitable in the support of manual control tasks. Continuous haptic feedback can be called haptic guidance, and it has been shown that it can improve manual control task performance in, for example, car-following [6], lane-keeping [7], and curve negotiation [8].

In this study the impact of continuous haptic steering guidance on curve negotiation behavior is investigated. We propose a haptic guidance system based on a preview controller, which generates smooth, continuous forces. Curve negotiation behavior with and without the haptic guidance will be tested on a single track with varying curvature.

It is hypothesized that the haptic guidance will lead to similar results as for the haptic gas pedal support we previously designed for car-following: slightly improved performance at reduced control activity. [6], [9].

The article is structured as follows. Section II describes the experiment protocol that was applied to investigate the effectiveness of our system. This is followed in Section III by...
the results of the experiment. Section IV discusses the results that were found. Conclusions are drawn in Section V.

II. METHOD

A. Fixed-base Driving Simulator

The driving experiment was performed using a fixed-base driving simulator, with passive brake and accelerator pedals, an actuated steering wheel, an LCD screen for dashboard information, and a wall on which a computer-generated driving scene was projected. The available dashboard information, and the brake and gas pedal were not used because the vehicle speed was fixed at 20m/s. The driving scene consisted of a two-lane road, which was projected by a Sanyo PLC-XU33 multimedia projector, yielding a 3.3x2.1m visual with 60° horizontal and 40° vertical field of view.

The simulation was updated at 100Hz; the visual scene was rendered at 50Hz. To improve speed perception, reflector poles lined the shoulder of the road, and trees were placed randomly along the road. Realistic engine sound was added to the simulation, and a seat shaker was used to convey the feeling of road-rumble while driving at a certain speed.

The actuated steering wheel (Moog-FCS S-motor) was controlled with a dedicated control loading computer running locally at 2500Hz to allow for a smooth haptic sensation of realistic steering wheel dynamics. The actuator could also simulate haptic guidance torques (updated at 200Hz), and always generated self-alignment torques, which were simplified as a constant stiffness on the steering wheel (a reasonable approximation at the fixed driving speed with the relatively low curvatures and steering frequencies used in this experiment).

B. Haptic Guidance Design

The haptic guidance was based on the lateral error between the reference path (defined here as the lane centre) and the position of the vehicle at a certain time in the future. This ‘look-ahead time’ principle was used previously to enable stable vehicle control [8], [10], and [11]. In this study the look-ahead time was set at 0.7 seconds and the resulting vehicle position at this time was predicted by assuming a constant steering input during that time.

The magnitude of the torque was determined by scaling the predicted lateral error by a constant gain, $K_f$. When $K_f$ is set too low, the feedback torques will barely be noticeable by the driver, and are not expected to be beneficial. When $K_f$ is set too high, the feedback torques are expected to be so dominant that they will cause the steering wheel to turn automatically even when the driver takes his/her hands off. Since we aim to avoid task automation, the system’s force feedback gain $K_f$ was tuned such that it provided torques that are large enough to be helpful to the driver, but not large enough to allow automatic steering. This concept of shared control has been explored before by [7] and [12] in steering and by [13] in performance enhancement in virtual environments.

To illustrate the concept of shared control, we compared the curve negotiation performance of the haptic guidance forces without human input of several force feedback gains of the haptic guidance system. Fig. 1 shows that at high force feedback gains the haptic guidance feedback is well capable of automatically negotiating the curved trajectory in the experiment. However, it also shows that already for the low gain setting $K_f=2$, which was used in our experiment, performance with human input is improved to the level of the automatic controller with $K_f=8$. Thus, while keeping the human operator actively in the loop, the haptic feedback forces can assist in improving human performance without automating the control task.

Figure 1. Controller performance (RMS of lateral error) with different force feedback gains. The last two bars show the measured human performance with and without haptic guidance.

C. Subjects

The haptic guidance was tested on a group of 12 subjects (6 females, 6 males). All subjects were young drivers (mean age=25 years, $\sigma=2.1$), and considered to be experienced (drivers license $>5$ years, driving 15,000km/year on average). The subjects participated voluntarily, and received no financial compensation for their efforts.

D. Task Instruction

Drivers were asked to take place in the simulator and adjust their chair so they were comfortably seated as though expecting a long drive. They were instructed to keep both their hands on the steering wheel at all times, in a ‘ten-to-two’ position (see Fig. 2). Subjects were told to steer the vehicle comfortably through all upcoming curves and strongly requested to remain in right lane of the two-lane road and avoid crossing lane boundaries on either side. These instructions were emailed to them several days before the experiment and were repeated verbally by the experiment leaders on the day of the experiment.
E. Experiment Protocol

A two-lane road with a lane-width of 3.6m was used. The curvature profile was generated as a multi-sine to provide an unpredictable road, though with a clearly defined frequency content with bandwidth up to 0.2Hz (see Fig. 3). The left and right shoulders of the road were marked with continuous, solid white lines. The road centerline was marked by a dashed white line. Driving speed was fixed at 20m/s, so drivers could only negotiate the curves by steering.

F. Analysis

All data gathered for this experiment was sampled at 100Hz. A great number of variables were recorded in order to analyze the effects of haptic guidance on curve negotiation. Based on the measured data, the following dependent variables were calculated to determine curve negotiation performance, control activity, and control effort.

1) Performance: Curve negotiation performance was assessed by looking at lane keeping performance and time-to-line crossing. Lane keeping performance was defined by the root mean square error of the lateral deviation from the centerline of the right lane, RMS($e_{lateral}$), a common lane keeping metric (see, for example, [7], [8], [10], and [16]). The lateral error was defined as the distance between the middle of the own vehicle and the center of the right lane. A negative error represented a deviation to the left of the lane center, a positive error a deviation to the right of the lane center.

As a measure of how well drivers were able to follow the curvature of the track, the time-to-lane crossing (TLC) was determined. In literature a number of different methods is referred to by which the TLC can be calculated, see [17]–[19]. For this research, the ‘curved road, straight trajectory’ calculation of TLC, as described in [19], has been adopted. They find that this calculation of TLC yields smooth plots and presents good characteristics, though with delayed driver correction.

2) Control Activity: Standard deviation of the steering wheel angle, $\sigma(\theta)$, gives a good indication of low frequency control activity associated with road curvature [16]. Steering wheel reversal rate (SRR) was used to assess the more high-frequent control activity of drivers [16], [20]. SRR is reported by [20] to be related to task demand, though they argue that whether SRR increases or decreases with task demand depends on the level of task difficulty relative to the driver’s capacity to deal with it. Task demand in the experiment described in this article was expected to be low, while drivers were selected for being experienced. SRR can, therefore, be expected to low and decreasing with decreasing activity.

3) Control effort: Control effort is expressed as the standard deviation of the measured steering forces, $\sigma(F_c)$. Previous research with a haptic support system for car-following has shown that, when drivers adopt a force-task strategy in manipulating their controller, that is, when they try to actively yield to the presented guidance forces, the standard deviation of the measured control forces decreases [6], [9].

III. RESULTS

A univariate analysis of variance (ANOVA) was used to determine the statistical significance, between subjects, of the results of the experiment ($\alpha=0.05$). All dependent variables were checked for normality and homogeneity to ensure applicability of the test. Results were tested with a significance level $\alpha=0.05$. Significances of $p<0.01$ were considered highly significant; levels of $0.1<p<0.05$ were considered marginally significant.
A. Performance

All drivers displayed a very small (<0.04m) positive off-center mean lateral error, both with and without haptic guidance. The RMS of the lateral error (see Fig. 4) was found to decrease slightly, but significantly with the haptic guidance system turned on ($F_{1,11}=24.683; p<0.01$). This, in turn, yielded small, but significantly lower TLC for both the centerline as well as the right shoulderline of the right lane when the haptic guidance forces were present, see Fig. 5 (centerline: $F_{1,11}=46.200; p<0.01$; shoulderline: $F_{1,11}=16.569; p<0.01$).

B. Control Activity

Control activity is reduced significantly with the use of haptic guidance forces, though the magnitude of the change in standard deviation of the steering wheel angle ($\sigma_{\theta}$) is only a single degree, see Fig. 6 ($F_{1,11}=24.897; p<0.01$). More interestingly, the steering wheel reversal rate is reduced by approximately 10%, though this result is only marginally significant, see Fig. 7 ($F_{1,11}=5.629; p=0.037$).

C. Control Effort

The standard deviation of the steering forces increased substantially when haptic guidance is present, see Fig. 8 ($F_{1,11}=214.423; p<0.01$).

![Figure 4](image-url)  
Figure 4. Mean RMS of the lateral error for both conditions and 95% confidence intervals.

![Figure 5](image-url)  
Figure 5. Mean minimum TLC to the road centerline and the right shoulder marking for both conditions and 95% confidence intervals.

![Figure 6](image-url)  
Figure 6. Mean standard deviation of the steering angle for both conditions and 95% confidence intervals.

![Figure 7](image-url)  
Figure 7. Mean steering wheel reversal rate ($^\circ$ gap values) for both conditions and 95% confidence intervals.

![Figure 8](image-url)  
Figure 8. Mean standard deviation of the steering forces for both conditions and 95% confidence intervals.
The design choice of the force feedback guidance system based on future lateral error measured from the lane center has been a matter of debate in our group. Realistic driving behavior in curves includes cutting corners and driving with a constant offset from the lane center. The latter issue was not a large factor in our experiment: the results show that the mean driving position was only slightly off-center, with such a small margin (<0.04m) that it would barely be noticeable as a force offset on the steering wheel. It was expected that drivers would drive more off-center, but the explicit task instruction to subjects to stay in the right lane might have influenced this behavior. With respect to curve-cutting: our haptic guidance system naturally achieves this because of the look-ahead controller, which also cuts curves depending on the gain and look-ahead distance. Still, since we used a controller with constant settings for a road-profile with varying curvatures, some curves may have been taken with too little cutting, and some with too much: possibly leading to excessive peak forces.

The reduction of RMS($e_{lateral}$) found with haptic guidance, was also found in [7] (for lane keeping) and [10] (for curve negotiation), though we found a far smaller margin. Combined with the increase in TLC, for both lane centerline as well as the right hand shoulder of the road, this indicates that drivers drove more accurately along the lane centerline.

As hypothesized, the slightly improved curve negotiation performance was achieved with smoother control behavior. Both the standard deviation of the steering angle as well as the SRR decreased when using haptic guidance – a consistent result with the haptic guidance system for longitudinal control investigated in [6] and [9]. If, under the circumstances of the experiment, it can be assumed that SRR also is a measure of task load [20], then the performance increase is not only achieved with smoother control, but also with less demand from the driver.

The designed haptic was beneficial during the tested experimental conditions, but the increase in the standard deviation of the steering force indicates that the benefits came at a price. It remains to be investigated whether this was the result of our design choice of the haptic guidance (the gain and look-ahead time) or perhaps of an adaptation to the guidance system, with drivers using the guidance forces to “hang” into the curves, pushing the steering wheel comfortably against forces to be guided through the curve – very much like drivers use the self-aligning torque of the steering wheel in driving without haptic guidance. The latter explanation is perhaps more likely. During informal interviews after the experiment, most subjects reported liking the haptic guidance, finding it comfortable and useful. Still, the increased forces indicate that drivers were not agreeing with the haptic guidance, and counteracting it at some instances. A more thorough analysis of where this mismatch happened is expected to provide better insights, especially when compared to behavior during haptic guidance that is based on a more natural reference path (i.e., gain and look-ahead time that better match those of the driver).

There are several directions for future research that follow from this experiment. One concerns the possibility of guidance forces allowing automation. The force feedback gain $K_f$ was tuned to be low enough to establish a shared control environment for negotiating the curvatures used in this experiment. However at lower frequencies, for example, by driving at lower speeds, or for less sharp curves, the resulting torques may be high enough to allow for hands-off curve negotiation, that is, automation. The speed dependency of our haptic guidance forces is partially resolved by using a time-based look-ahead algorithm. The effectiveness of this look-ahead approach needs to be investigated further, though, as speed was fixed in this experiment.

Another direction to investigate is the interaction between speed control and curve negotiation. To facilitate analyses, the speed was kept constant in this experiment, and the curvatures were designed accordingly, to allow their negotiation at a constant speed. It is necessary to test the haptic guidance for different situations, in order to ensure its functionality beyond the current experimental conditions.

V. CONCLUSIONS

Haptic guidance forces on the steering wheel were investigated as a means for driver support during curve negotiation. Curve negotiation performance was improved with less steering activity compared to driving the same track without haptic guidance.

Contrary to the findings in research on longitudinal haptic guidance, the standard deviation of the steering forces increased with haptic guidance forces present, indicating a mismatch between the drivers desired steering actions and those of the guidance system. All subjects still reported to appreciate the guidance, which also objectively shows in smoother steering behavior.

Future research will focus on a better matching of guidance forces to natural driving behavior, in order to further improve the guidance system; and with that, human curve negotiation behavior.

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