Force Feedback in a Stationary Driving Simulator

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ABSTRACT

This paper describes three experiments conducted in a driving simulator that explore how force feedback information may be used by the driver. We simulated two types of driving situations, a relaxed driving situation and one that is more demanding, to see how steering torque information affected the variance of the steering movements. The results show that the addition of steering torque decreased steering variance when the driver is controlling the vehicle after a turn or skid. A hypothesis of how drivers use the torque information is also suggested.

1 INTRODUCTION

As practical active feedback systems become more prevalent in the automobile industry, it becomes increasingly necessary to understand what information the human driver is already perceiving while controlling the vehicle. With such an understanding, a safe and effective active feedback system can be designed and implemented which seamlessly aids the decision making and driving behavior without displacing any relevant information that is already present. For example, a power steering system described by Nakamura et al. [1] adjusts its output to fit the style of driving. However, the best characteristics for any particular situation are still difficult to ascertain. With careful consideration of the driver's behavior, it may be possible to avoid the problems such as those that have been reported with anti-lock braking systems (ABS) where very little safety gain has been realized possibly because drivers still use the ABS like conventional brakes, i.e. using a pumping action [2]. Additional feedback might have been useful to help the driver change their behavior.

Although drivers obtain a substantial amount of information for driving from vision, information from other sensory modalities may also provide relevant information about the state of the car or even the surrounding environment. Gordon [3] found that other sensory inputs such as steering wheel feel and transverse acceleration ("seat-of-the-pants" feel) were ranked in importance by drivers just after vision of the road ahead. Also, as more devices with visual interfaces, e.g., navigation systems, are introduced into the vehicle it is likely that the visual sensory channel may become overloaded. By distributing information through the other sensory modalities such as audition or kinesthetics, it may be possible to spread the cognitive load on the driver over a greater pool of resources.

The steering wheel is one possible device through which artificial feedback information could be provided. In fact, an active steering wheel was studied in depth by Schumann [4] as a possible interface for a collision warning system. A major motivation for their use of the steering wheel as a display was the concept of stimulus-response compatibility [5]. This concept suggests that if the information receptors also serve as the effectors of the response then error rates and response times might be improved. But it is important to consider what information is already being obtained through the information receptors, so that the artificial feedback does not disrupt the information flow. So, with respect to devices implemented through the steering wheel, an important question to ask is "What sort of information does the driver get through the steering wheel?"

Previous Research

According to Gordon [3] the steering "feel", or torque feedback at the steering wheel of a car, was one of the highest rated inputs after vision. Segel [6] performed one of the earliest studies of the effect of steering torque on a driver's control of a vehicle, concluding from his results that drivers relied on steering-feel information to help steer. Although driving performance was not quantitatively measured, the subjects' impressions of the various steering torque conditions and their effects on the handling of the vehicle were reported. Some interesting conclusions relating to steering torque were: (1) If the torque gradient is too low, the driver has difficulty positioning the steering wheel, and (2) the precision of steady-state turns is less sensitive to torque gradient than passing maneuvers. He also suggested that the degree to which the steering feel affects driving is dependent upon the type of control strategy used to drive, either "free-

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control" driving which is relaxed or "fixed" control which is a high gain state.

In quantitative studies of driving performance, the addition of steering torque seems to have a small effect on driving performance. Hoffmann and Joubert [7] found that changing between two different levels of steering torque (6 and 45 lb-ft/g) in a real car did not have a significant effect on performance when driving on a curving course. Performance was measured by the number of times the vehicle touched any of the cones defining the edges of the road. In a later study [8], they found that drivers were fairly sensitive to changes in vehicle handling characteristics, e.g., response time, stability, and steering ratio. The subjects might have been able to detect these altered characteristics from the resulting steering torque changes. In studies conducted on a driving simulator, Godthelp [9] tested the effect of three steering torque gradients (0, 9.0, and 17.9 Nm/rad) on steering wheel movements in a lane changing task and found that the steering torque decreased the deviation of steering wheel amplitude. This supported his earlier hypothesis [10] that torque reduces steering variability in precognitive or "open-loop" tasks.

In this paper, we begin examining how the torque that is sensed at the steering wheel may help the driver maintain control of the vehicle. The variance of the steering movements was used to evaluate the driver's performance. An examination of the physical variables that contribute to the torque, e.g., lateral acceleration of the car, forward torque of the drive wheels, road surface conditions, etc., shows that a lot of information might be perceptible through the steering wheel. However, it is likely that the driver does not maintain a complex model of the vehicle dynamics. Instead, the driver may adopt a few simple strategies for interpreting the torque information to aid driving.

The goal of the experiments in this paper is to quantify and compare the effects of steering torque on the two driving states suggested by Segel. The first task, driving on curving road, can be negotiated in a relatively relaxed manner or under "free- control". The second task, returning to the road after a skid, is a task that occurs at a quicker pace and is more demanding. It represents a condition where "fixed control" is used. Both of these tasks require visual and, possibly, force feedback, so they are not "open-loop" tasks.

2 DRIVING SIMULATION

Hardware/Software

The experiments in this paper have been conducted on a fixed base driving simulator, where it is possible to directly control the steering torques as well as the environment surrounding the vehicle. The CBR simulator consists of a Nissan 240SX convertible (truncated behind the front seats) positioned in front of a wall upon which the driving scene is projected. The projected image is generated by a SGI Indigo^2 Extreme and subtends approximately 60 degrees horizontally and 40 degrees vertically. The "engine" of the 240SX is a 486 PC which handles the digital I/O for the instrument panel and input control devices, such as the steering wheel, accelerator pedal, and brake pedal. The state of these devices and the parameters of the car model (described below), are recorded in an output file.

The steering torque is generated by an AC motor which is directly attached to the steering column under the hood. The steering wheel position is measured by an optical encoder also connected to the column. Closed loop control is accomplished through the position control algorithms of the Motion Engineering, Inc., 4-axis DSP-based motion control board mounted in the 486 PC under the hood. The current amplifier/motor combination can generate a peak torque of 5.67 Nm and a continuous torque of 2.8 Nm. These torques are limited by the output of the current amplifier and not the motor, so it is possible to increase the steering torque by replacing the amplifier. However, in our experiments, we increased the steering torque by attaching four coil springs in parallel to the steering column. The four springs approximately doubled the torque on the steering wheel to about 8 Nm.

Modeling steering torque

The actual computer model of the vehicle is based on a Nissan 240SX coupe, a two-door rear-wheel drive enclosed version of the convertible. The steering force feedback takes into account lateral tire friction, angular momentum (as related to vehicle velocity), vehicle inertia and lateral acceleration. The steering force feedback increases non-linearly with respect to the aforementioned variables and has a limit at which point the tires slip and vehicle skid ensues. During vehicle skid, the magnitude of the steering force is noticeably reduced and the sound of skidding tires is activated to further emphasize the condition of vehicle skid.

Under ordinary non-emergency driving conditions, the typical range of steering torques is between 0 and 2 Nm. In all conditions, the range extends up to approximately 15 Nm [4]. Measurement of the torques in the simulator indicates that the normal operating range for the motor was approximately 0 to 3.5 Nm. For our experiments, the greatest torque experienced was measured at around 5 Nm. This should be sufficient for simulating the relaxed driving conditions, but the steering might feel "light" in the more demanding conditions.

3 METHODS

Experiment One

In this experiment, we tested whether the presence of a torque gradient would change driving performance as measured by the variance of the steering angle. The driving task was to traverse a road with three sets of opposing turns of various curvatures (Fig. 1). The three radii of curvature were 30m, 45m, and 60m, and the straight sections connecting the curves were 100m in length. The lane width was 4m. The order of the curves was randomized to form three different tracks. Twelve subjects, all licensed drivers, participated in this initial experiment. Each subject was presented with the same order of experimental conditions and drove the tracks in the same order (Track 1-Track 2-Track 3). In addition to the three different curvatures, we manipulated the steering torque (no torque/torque from motor) and the speed (40 mph/55 mph/self-controlled). The data from the self-controlled speed trials were not analyzed because the differences in speed profile made comparison extremely difficult. The subjects were instructed to stay in their lane and to return as quickly as possible if they drove out of the lane. There were no other objects or traffic in the simulation. The subjects' performance was measured by the variance in the steering angle in these sections. This measure should reflect the stability of the subjects' steering movements while driving through the course. The performance was measured in two types of segments: (1) in the curve, and (2) in the first 70m of a straight segment following the curve. In general, the subjects were able to position the car back in the lane after 70m.

Experiment Two

In a follow-up experiment, we examined whether the torque gradient profile also affected the steering behavior. Thus, three torque conditions were examined: no steering torque, torque from the springs, and combined torque from the springs and motor. The subjects drove along the same three roads as in the previous experiment and drove only at the fixed speeds of 40 mph and 55 mph. The presentation order was randomized for each subject. Unfortunately, only four subjects were tested before the springs were damaged during a demonstration outside the experiment. These four subjects did not participate in the first experiment.

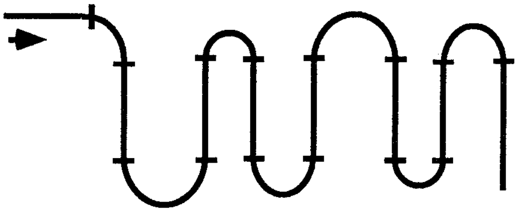

Figure 1: Top view of the first road driven by the subjects. Two other roads were created by changing the order of the curves. The arrow indicates the direction of travel.

Experiment Three

In this experiment, we tested whether the presence or absence of steering torque affected the drivers' ability to recover quickly from a skid. This driving task is representative of Segel's "fixed-control" driving in contrast to the "free-control" situation of Experiments One and Two.

The driving task in the third experiment required subjects to negotiate a sharp curve (R=15m) at a speed which would cause the car to skid. The path was no longer defined by a traditional road, but instead, a line of small posts defined the path to be followed. The subjects were instructed to drive over as many of the posts as possible, so that they would return to the path after skidding as quickly as possible. Although the subjects controlled their own speed, they were also instructed to attain a speed of between 40 and 50 mph before entering the curve. The same twelve subjects from Experiment One participated in this experiment. Two steering torque conditions were tested (No torque/torque from the motor) and each subject tried the task a total of six times alternating between each condition. The variance of the steering angle was again measured. The variance was computed after the vehicle had stopped skidding and as the driver was returning to the prescribed path after the curve.

4 RESULTS

Experiment One

The results show that during the duration of the curves there was no difference between the steering angle variance for the two torque conditions (No torque/Torque from motor)(Fig. 2). Not surprisingly, the radius of curvature has a significant effect on the steering angle variance ($F=148.9$, $p<0.001$); variance decreases as the radius of curvature increased. The speed does not have a statistically significant effect.

There is a small but significant difference in steering angle variance due to the torque in the straight segments following the curves ($F=10.7$, $p=0.007$).

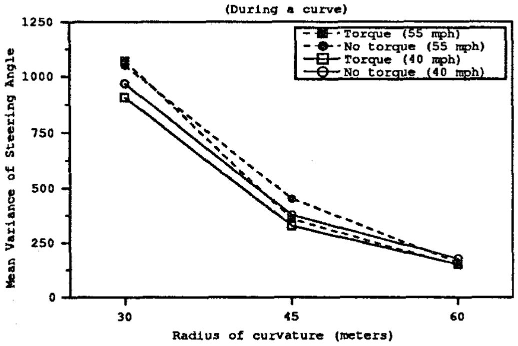

Figure 2: Variance of steering angle during the curves . There is no significant difference in performance between the torque conditions (Circles - No torque; Squares - torque from motor). The open symbols are data for 40 mph trials, filled symbols for the 55 mph trials.

The test results without force feedback show the drivers overcorrecting their steering and performing mild weaving patterns as they exited the sharp curves. The tests with feedback show drivers exiting the curves with little extraneous steering correction. Figure 3 shows the mean steering angle variance in the 70m of the straight segments immediately following the various curves. The torque effect is significant for steering variance following the 30m radius curves on Track 1 (F=8.0, p=0.015) (Fig. 3, top) and Track 2 (F=6.4, p=0.027) (Fig. 3, middle). However, by the last trial set (driven on Track 3), there is no significant difference between the performance in either torque condition (Fig. 3, bottom). There is also a significant effect from the curvature of the preceding turn (F=13.5, p<0.001).

Experiment Two

In this experiment, no significant effect due to the different levels of torque is found. Figure 4 shows representative plots of the data for variance during the curve (top) and in the segment after the curve (bottom). The steering angle variance in the straight segments following the sharpest turn is slightly smaller than in the previous experiment. The four subjects who participated in the experiment had previously driven in the simulator as subjects for other studies. Their experience might have helped them adapt to the different torque conditions before changing tracks.

Experiment Three

The results show that the addition of torque produced a significant improvement in driving performance (F=13.0, p=0.004) after recovering from the skid (Fig. 5). The greatest difference occurs for

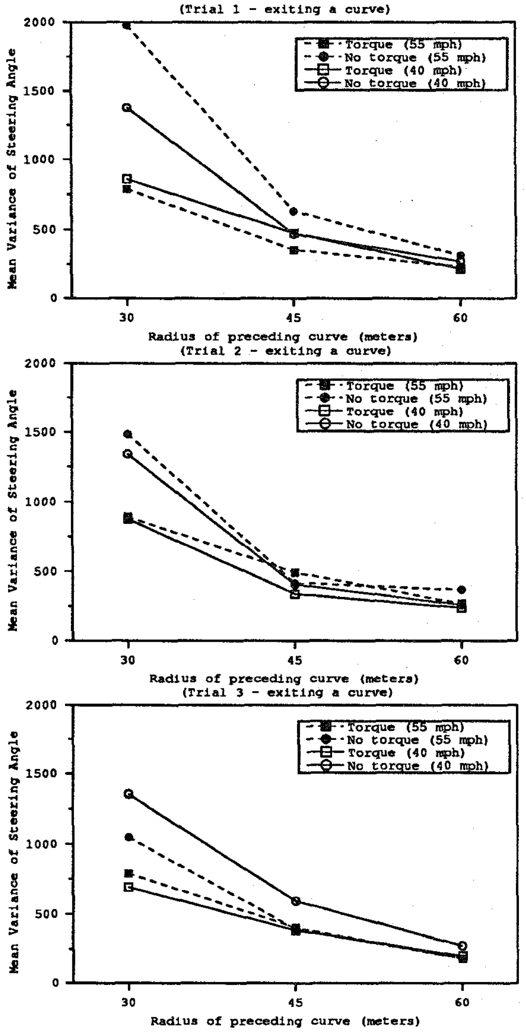

Figure 3: Variance of steering angle in the straight segments following the curves. The performance on the first, second, and third trials are shown in the top, middle, and bottom plots respectively. There is a significant difference in performance after the sharp curves, but not for the long turns. Note that the difference in performance following a sharp curve decreases by the third trial (Track 3) driven.

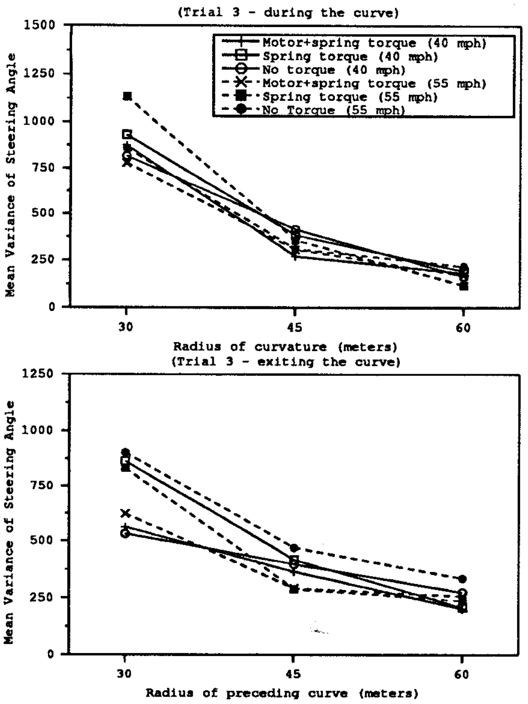

Figure 4: Representative plots of steering variance for three torque conditions during the curve (top) and following the curve (bottom).

the last trial (Trial 3). Trials where the subject became disoriented after the skid (3 cases) or where the car did not skid at all (2 cases) were excluded from the analysis. The variance in steering angle when torque is not present is twice as large as when torque is present. When the force feedback was disabled, the subjects had trouble returning cleanly to the prescribed path after correcting their skid; subjects overshot the path and then had to turn back to return. With the force feedback enabled, subjects were able to return directly to the prescribed path after correcting their skid. None of the subjects overshot the path with the force feedback enabled.

5 DISCUSSION

The results are in general agreement with Segel's observation that the addition of torque had less of an effect in steady state turns compared to passing maneuvers. In Experiment Three, the results clearly show that the addition of steering torque in the simulation decreased the variance in steering movements. During the curves in Experiment One, there was no effect. However, it is interesting to note that there is a slight performance improvement with the addition of torque in the straight sections following the curve. The steering movements in both cases are similar. This result may shed some insight into how the torque information might be used by the driver.

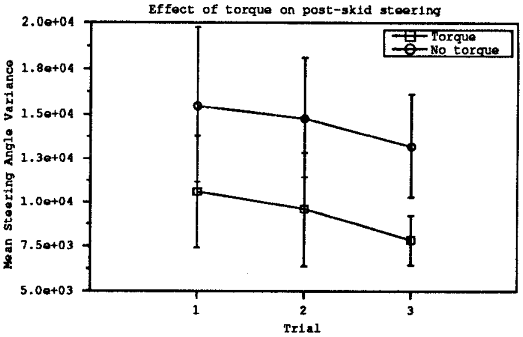

Figure 5: Variance of steering angle during the recovery from a skid. The error bars represent the standard error of the mean.

Consider that in making turns of constant radius, as the curves used in Experiment One, the driver tries to find a fixed position that will generate an appropriate path through the turn. Whether the torque is present or not, the driver must sense a proper position for the steering wheel. Psychophysical experiments by Schumann [4] indicate that people are not particularly sensitive to torque differences under 2 Nm. Thus, in negotiating a curve, it will be difficult to judge the correct position from the changes in torque, unless the gradient is very steep. Therefore, there is little difference to the driver whether torque is present or not. However, when exiting the turn, or returning to the road after a skid, the eventual desired position of the steering wheel is at the central position where torque is at a minimum. Also, as the driver crosses the central position, the sign of the direction of the torque is different on either side of the central point. With this additional information, the driver might be able to localize the central position better than any other location. In actual vehicles, there is some hysteresis which would add some uncertainty to the central position [11], but the basic torque information would still be present. A psychophysical investigation of the perception of torque and steering position would be helpful to determine if this strategy is actually used.

Although the simulator had a smaller torque range than normal driving, a significant torque effect was present in the skid recovery experiment. This suggests that the exact profile of the torque gradient is not an important source of information for ordinary drivers. In automobile racing, however, other driving techniques involving drifting and sliding are utilized, and in these cases, the feel of the steering is probably much more critical [12]. Racing drivers must monitor and modulate the state of their car through their steering movements very precisely to avoid crashing or losing speed.

Another possible role of the steering feel that was not explored in this paper is in adapting the driver to the dynamics of a new car. People seem to easily adapt to driving a new car, such as a rental, without a long learning period. Does the steering feel have a role in providing information to the driver how to change their control strategy? The results of Experiment One do show some learning effects that occur relatively quickly, i.e., on the order of twenty minutes of driving. The four subjects in Experiment Two had previous experience with the simulator, thus their performance was essentially the same from beginning to end.

6 FUTURE RESEARCH

The next step will be continue the study whether the shape of the torque profile is even perceptible by the driver and how it may affect driving performance. Further exploration of the importance of the exact shape of the torque gradient will also be completed. This will involve some psychophysical experimentation as well as further modeling of the steering system. With respect to driving simulations, this research will help clarify the basic requirements for a system that will be used to study driving behavior. Furthermore, it is hoped that this direction of research will be useful in the development of future active feedback systems in automobiles. By understanding the information that is obtained in present vehicles, it will be possible to more effectively augment the current capabilities of the driver.

7 ACKNOWLEDGEMENTS

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