A Study of the Effect of Steering Force Characteristics on Steering Feel

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ABSTRACT

Many studies indicate that steering force characteristics influence steering feel and driver-vehicle closed-loop response. This study investigated the influence of steering force characteristics for ordinary drivers who drive by commuting, leisure or shopping, not professional test drivers, using a stationary-type driving simulator. Steering force characteristics were evaluated by changing the non-linearity of the steering angle-the steering torque and hysteresis without changing the vehicle response to the steering angle. The influence of these characteristics was evaluated based on the vehicle response, electromyography recording and subjective evaluation by the drivers. The electromyography results show that drivers can steer most smoothly when the steering force characteristics with moderate nonlinearity and hysteresis. However, some drivers in this study subjectively preferred the linear steering force property.

Keywords: Steering feel, Vehicle dynamics, EMG, APDF, Subjective evaluation

1. Introduction

Steering feel is an important characteristic for vehicles and, therefore, many studies on the topic have been conducted. Vehicle’s steering feel are developed by suspension tuning and calibration of electric power steering (EPS) based on subjective evaluation by experienced test drivers as well as the objective evaluation criteria. However, the developed steering feel may not be appropriate for ordinary drivers in terms of the driver-vehicle closed-loop performance, in terms of the driver-vehicle closed loop performance, ease of driving or driving pleasure. Therefore, some studies examine steering feel based on customer demands (Schick et al., 2006) (Badiru, 2014). Other studies have evaluated ease of steering using electromyography (EMG) by changing the vehicle response to the steering angle (Kuramori et al., 2000, 2002) or steering direction (Mizuno et al., 2012). However, many papers studies emphasize that the steering force characteristics influence the steering feel and driver-vehicle closed loop response (Yamada et al., 2013). This study uses a different approach to evaluate the steering feel or ease of steering under various steering force characteristics for ordinary drivers, using a stationary-type driving simulator. A combination of three evaluation methods was applied for this investigation.

2. Method

In this study, steering force characteristics were evaluated by changing the non-linearity of the steering angle-steering torque relation and the hysteresis without changing the vehicle response to the steering angle. Fig.1 shows four sets of steering force characteristics, as described below.

(1) Four types of steering force characteristics:
   Case #1: Linear characteristics
   Case #2: Nonlinear characteristics
   Case #3: Moderate nonlinear characteristics
   Case #4: Moderate nonlinear characteristics

Case #1– Case #3: With hysteresis width.
Two types of driving courses, as shown in Fig. 2 with an S-curve or an L-curve were used for the investigation. Ten drivers drove on Course #1 and five drivers (male students aged 21-24 who drive regularly) drove on Course #2 at a constant speed of 60km/h. We obtained informed consent from every driver in this study.

**3. Evaluation Method**

The steering feel was evaluated using the three methods listed below:

1. **EMG as a biomedical-signal.**
2. **Steering behavior and response by the drivers.**
3. **Subjective evaluation by the drivers.**

**3.1 Evaluation using EMG**

The mean-value and the root-mean-square deviation of percent maximum voluntary contraction (%MVC) were evaluated. The measured data are as follows (Takahashi et al., 2013).

![Figure 1. Steering force characteristics for investigation](image1)

**Figure 1.** Steering force characteristics for investigation

(2) Two types of driving courses, as shown in Fig. 2 with an S-curve or an L-curve were used for the investigation.

Ten drivers drove on Course #1 and five drivers (male students aged 21-24 who drive regularly) drove on Course #2 at a constant speed of 60km/h. We obtained informed consent from every driver in this study.

![Course #1: The deltoid front section, which acts in the direction of steering as an agonist.](image2)

**Course #1:** The deltoid front section, which acts in the direction of steering as an agonist.

![Course #2: Extensor carpi radialis longus, which acts in the opposite direction of steering as an antagonist.](image3)

**Course #2:** Extensor carpi radialis longus, which acts in the opposite direction of steering as an antagonist.

Amplitude probability distribution function (APDF) analysis (Hagberg, 1979; Tomioka, 2001; Ishihara and Oguri 2015) was also applied to evaluate the EMG signals.

![Figure 3. Attached EMG sensors](image4)

**3.2 Evaluation of the Steering Behavior**

Variations in steering behavior were used as quantitative evaluation criteria. As shown in expressions (1) and (2), the mean-square value of the steering angular velocity and yaw acceleration were used as the criteria. These values were calculated throughout the course and in the following sections: increasing steering (defined as steering from straight driving to turning), steering transition from left turn to right turn and decreasing steering (from turning to straight driving).

\[
SV_{\theta,\text{avg}} = \frac{\sum (d\theta)^2}{n} \tag{1}
\]

\[
YA_{\text{avg}} = \frac{\sum (dr)^2}{n} \tag{2}
\]

where \(\theta\) is the steering angle and \(r\) is the yaw velocity.

![Figure 4. Measuring the steering angle and %MVC. Sect. 1: Increasing steering, Sect. 2: Transition from left turn to right turn, and Sect. 3: Decreasing steering.](image5)
3.3 Subjective Evaluation

Drivers evaluated the steering force characteristics on a visual analog scale ranging from 0 to 10 points. Simultaneously, the drivers answered the questions shown below, (considering that ordinary drivers are not familiar with the evaluation of steering feel).

1. Course #1: Are you able to steer easily and steadily?
2. Course #2: Is the steering feel good?

We adopted a method of paired comparison for the data obtained from Course #2, comparing each case with Course #3 which had the lowest muscular load based on a survey review.

4. Results

4.1 Results of the EMG Evaluation

Case #3, which has moderate non-linearity, was associated with the lowest muscular load in the subjects. In order of muscular load, Case #4 > Case #2 > Case #1 > Case #3, as shown in Fig. 5. From the perspective of stability, Case #3 showed the most stable steering. The order of stable steering is Case #3 > Case #2 > Case #4 > Case #1, as shown in Fig. 6. The results of Case #3 showed smoothest steering. Thus, the steering force characteristics that had a moderate non-linearity and hysteresis width were optimal for ordinary drivers.

4.2 Results of the Steering Behavior Assessment

During increasing steering (Sect.1 in Fig. 4), the fluctuation in the steering angle was high in Case #4, and it was same in Case #2, Case #3 and Case #4. During decreasing steering (Sect. 3 in Fig. 4), the Case #4 showed a larger fluctuation in the steering angle than the other cases having hysteresis width (Fig. 7). During decreasing steering the data indicate that hysteresis contributed to a stable steering response of the drivers. The root-mean-square value in Case #1 and Case #4 during each section were not stable on Course #2 (Fig. 8). The amount of the fluctuation depended on the course, but steering angle fluctuation was confirmed to increase during the severe driving task having the steering transition.

Based on the data, the non-linear steering force characteristics when hysteresis is present, as in Case #3 and Case #2, include a lower level of fluctuation in steering angle. Only the steering behavior evaluation results are shown, because the vehicle response heavily depends on steering angle.

4.3 Results of Subjective Evaluation

The subjective evaluation results were normalized by the value of the Case #3, which had the smallest muscular load. As shown in Fig. 9 and Fig. 10, Case #2 and Case #4 had lower evaluation in both courses, and the evaluation values for Case #1 and Case #3 were higher. However, as shown
in Fig. 10, on Course #2, the evaluation values for Case #1 was highly regarded even though it was associated with higher muscular load than Case #3.

5. Conclusion

This study determined that drivers can steer more smoothly with less muscular load when driving vehicles with moderate nonlinear steering force characteristics and hysteresis, based on the analysis of EMG and steering behavior. The steering force characteristics without hysteresis induced higher muscular load and steering angle fluctuations, in the subjects, particularly during decreasing steering. These results agree with the subjective evaluation of the moderate non-linear steering force characteristics with hysteresis by the test drivers. These results confirm that the steering force characteristics preferred by the test drivers were also favored by the ordinary drivers from a physiological point of view. Such desirable steering force characteristics are expected to reduce the physical load on drivers and improve the ease of driving for ordinary drivers. However, some drivers subjectively prefer linear steering force with hysteresis to the moderate non-linear steering force, despite showing higher muscular loads and being unable to steer smoothly, as measured objectively. This result supports the idea that different elements are required for the subjective assessment of the steering feel.

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