Evaluation of Acceptability of Steering Support Method Using Impedance Control with Multiple HMIs

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Abstract. In order to realize safer driving, it is necessary to operate the driving assistance device a few seconds before the car falls into a dangerous situation, and it is necessary to improve the acceptability of the driver. Therefore, a driving support system that improves acceptability and safety is needed. In this study, we introduce multiple HMIs into the steering intervention support system introducing the impedance control of the steering torque command, we aim to evaluate safety and acceptability in this system. We use the damping ratio as an evaluation index to derive control parameters that compatible with safety and driver acceptability at the time of steering intervention assistance. We conducted experiments using driving simulation and achieve the above object in the introduction situation of HMI.

1. Introduction
Currently, research and development of various Advanced Driving Assistant System (ADAS) for improving the safety of vehicle and Human Machine Interface (HMI) aiming at extending the period of driving and contribute to enhancement of driving skills are actively conducted. However, it is regarded as a problem that the safety of the vehicle and the drivability of the driver are deteriorated due to the interference between the ADAS performing the steering support and the driving operation of the driver [1]. In addition, when the authority of both the driver operation and the support system are mixed, it is necessary for the driver to understand the intention of the support system as a main task of the HMI, and realize safe driving in cooperation of both operation inputs. Toward the development of vehicle safety, it is necessary to establish ADAS and HMI that are useful for compatibility of safety and driver acceptability. So, Inoue et al. Determined the amount of steering torque that could correctly guide parked vehicle avoidance to improve driver acceptability[2]. And another study improving steering assist based on shared control type steering assist system was carried out[3], too. But, In steering torque command type steering assistance, it has been confirmed that the elderly driver is burdened even if it is moderate steering support [4]. Therefore, it is necessary to introduce a new steering assistance method instead of the existing steering torque command type steering assistance. To solve this purpose, the authors proposed to introduce impedance control into a driving assist system that cooperates with the driver and the vehicle, and introduce a damping ratio as an evaluation method for impedance parameter setting, and showed its effectiveness in experiment [5][6], also showed the effectiveness in other driving tasks [7]. However, It has not been verified whether it is effective to support other HMIs before steering assistance is added in order to improve acceptability and safety.

In this paper, we add support notice by sound effect as a new auditory HMI to steering assistance system using impedance control which is haptic HMI. In that case, we verify how the acceptability of the driver system changes and verify the effectiveness of the advance notice by HMI by clarifying the damping ratio that improves the acceptability. We report on the result of examination of the
acceptability based on questionnaire evaluation which is subjective evaluation and driving steering data which is objective evaluation by running experiment using Driving Simulator (DS).

2. Methodology

2.1. Steering Assist Algorithm
The driving support system used in this study assumes that the steering target angle \( \theta_t \) [rad] for steering support is given from the super supervisor type cooperative control system shown in Reference [8]. Based on this, the steering assist torque \( \tau_a \) at the time of steering support becomes as shown in the Figure (1).

\[
\tau_a = D_a \dot{\theta} + K_a (\theta - \theta_t)
\] (1)

We proposed the steering assist method to apply the equation of (1) to the steering in Reference [6]. Where the applied viscosity coefficient is \( D_a \) [Nm·s/rad], the applied spring constant is \( K_a \) [Nm/rad] and the target steering rotation angle is \( \theta_t \) [rad].

The steering dynamics during normal driving is expressed as (2).

\[
J_m \ddot{\theta} + D_m \dot{\theta} + K_m \theta = \tau_h
\] (2)

The inertia of the steering is \( J_m \) [kg·m²], the viscosity coefficient is \( D_m \) [Nm·s/rad], the spring constant is \( K_m \) [Nm/rad], and the applied torque to the steering of the driver is \( \tau_h \) [Nm]. The friction term was neglected. During normal driving, the steering torque felt by the driver is only the dynamics of vehicle steering system, as shown in Figure 1 (a), which is represented by (2). However, by applying the proposed steering assist torque \( \tau_a \) to the steering, the equilibrium point due to the viscosity term change and the spring term is added, and the dynamics felt by the driver as shown in Figure 1 (b) is changed. The proposed steering assist is performed by changing the dynamics using the impedance control.

![Figure 1: Steering dynamics](image)

2.2. Acceptability evaluation index using damping ratio
The impedance parameter of the steering mechanism part differs from vehicle to vehicle, and it is troublesome to set the applied viscosity coefficient and the applied spring constant that increase the driver acceptability. Since there are an infinite number of combinations of applied viscosity coefficient and applied spring constant, we want to make it easy to derive with a single evaluation index. Therefore, by using the damping ratio based on the steering dynamics at the time of steering assistance (that is, the state in Figure 1 (b)) as an evaluation index, a unified evaluation method not affected by the difference of the steering mechanism section for each vehicle is proposed [6], we will also use this in this paper. The damping ratio of the steering dynamics during steering assist is obtained as (3).
In this study, we evaluated the acceptability based on the damping ratio during steering assist.

2.3. Experimental equipment
Figure 2 shows the construction of our DS. This DS has constitution of a steering device simulating EPS directly connected to direct drive motor (DD), servopack, accelerator, brake, driver's seat, three displays, PC, speaker and sub monitor. The PC calculates the dynamics of the vehicle based on the driver operation, to present the virtual image and effect sound information based on the calculation. In addition, a torque command value calculated by impedance control described in section 3.2 is sent to the servopack, and the DD motor is controlled with a control period of 3 ms. The DD motor used in this steering device has a rated torque of 5 Nm (maximum 15 Nm) and an encoder resolution of 18 bits.

![Configuration of DS](image)

**Figure 2**: Configuration of DS

2.4. Steering control system configuration
The steering device using the direct drive motor used in this DS implements impedance control to reproduce the steering dynamics of the car. The dynamics of the constructed steering device is approximated as (4).

\[ J \ddot{\theta} + D \dot{\theta} = \tau_h - \tau_m \]  \hspace{1cm} (4)

The steering rotation angle is \( \theta \) [rad], the inertia of the device is \( J \) [kg·m²], the viscosity coefficient is \( D \) [Nm·s/rad], the friction is \( F \) [N], the command torque to the motor is \( \tau_m \) [Nm]. The normal steering dynamics of the automobile which the driver wants to let the driver feel when the driver operates the steering wheel is (2). By deleting \( \tau_h \) from (2) and (4), (5) is derived.

\[ \tau_m = (J_m - J) \ddot{\theta} + (D_m - D) \dot{\theta} + K_m \theta \]  \hspace{1cm} (5)

By controlling \( \tau_m \) obtained from (5) as the command torque of the motor, the steering dynamics is reproduced in this DS during normal driving. A list of impedance parameters to be used is shown in Table 1. In the case of this experiment, by modifying (4) to (6), the steering assist torque term \( \tau_a \) at the time of steering support is added, and the sum of \( \tau_m \) and \( \tau_a \) becomes command torque to motor.

\[ J \ddot{\theta} + D \dot{\theta} = \tau_h - (\tau_m + \tau_a) \]  \hspace{1cm} (6)
2.5. Experimental conditions
In this paper, we will cover situations where multiple HMIs were introduced for intervention support in avoiding parked vehicles in the same situation as the Reference [7], in which the driver misses the car ahead. As in Reference [5] to [7], this experiment is not an emergency avoidance support because it assumes pre-reading driving support to secure vehicle safety earlier in advance.

Subjects drive straight on the left side of the narrow road and perform avoidance operation of stopped vehicles simultaneously with steering assist. Figure 3 shows the driving environment in this DS. It assumes an urban area straight road with a one-way road width of 7.0 m, and running speed is fixed to 30 km/h. As in Reference [5], parked vehicles in front are not displayed as being overlooking the parking vehicles in front. In this experiment, in order to operate the steering intervention support on all subjects under the same conditions, we explained to the subjects about the situation where the support occurs and instructed the subject not to perform a prior deceleration or evasive action. Also, during the experiment, the subject grips the steering wheel with both hands and instructs not to release the hand from the steering wheel.

2.6. Impedance parameter setting of steering assist
The impedance parameters of the steering system in the normal state were set to the values shown in Table 2. The applied spring coefficient $K_a$ corresponds to the assist force at the time of intervention assistance, but here as two kinds of strong and weak assist force, as two patterns of 5.75 and 11.5 Nm / rad. The damping ratio $\zeta$ was set to 6 patterns of 0, 5, 10, 15, 20, and 25. From these values and equation (3), we derived the corresponding applied viscosity coefficient $D_a$ and set it in the steering system control system during the experiment. A summary of the parameters used in this experiment is shown in Table 3.
Table 2: Impedance parameters

| Variable | Value               |
|---------|---------------------|
| $J$     | 0.03 [kg m$^2$]    |
| $D$     | 0.01 [Ns/rad]      |
| $J_m$   | $J + 0.001 [kg m^2]$ |
| $D_m$   | $D + 0.3 [Ns/rad]$ |
| $K_m$   | 0.45 [Nm/rad]      |

Table 3: Impedance parameters at steering assist

| $K_a$=5.75 Nm/rad | $K_a$=11.5 Nm/rad |
|-------------------|-------------------|
| $\zeta$           | $D_o$             | $\zeta$           | $D_o$             |
| 0                 | 0                 | 0                 | 0                 |
| 5                 | 4.07              | 5                 | 5.77              |
| 10                | 8.44              | 10                | 11.84             |
| 15                | 12.82             | 15                | 17.92             |
| 20                | 17.20             | 20                | 24.00             |
| 25                | 21.57             | 25                | 30.07             |

2.7. Information presentation by HMI

The HMI to be newly installed in this experiment was sound effect. Table 4 compares the HMI introduction situation between Reference [7] and this study. Haptic HMI indicates steering support, and auditory HMI indicates advance notice by sound effect. Here, the effect sound is generated 1 second before the intervention of the steering support intervention, and this is defined as an advance notice sound in this paper, and the subjects are told that advance notice sound by the effect sound is carried out beforehand to the subjects. Furthermore, when the steering support intervention is performed, a sound effect different from the advance notice sound is generated.

Table 4: Introduction status of HMI

| Research                | HMI          | Auditory |
|-------------------------|--------------|----------|
| Previous research[4]    | Installed    | None     |
| This research           | Installed    | Installed |

2.8. Subjective-objective evaluation items

The subjects of the experiment are 8 men in their twenties. In this experiment, each time we avoided the stop vehicle, I asked them to answer the following subjective evaluation items. The subjective evaluation items are two items (A) easy steering operation, (B) thinking this steering assist is good. Evaluation items were all absolute evaluations, and they were asked to answer at 5 stages (-2, -1, 0, +1, +2) centered on the score 0. Each of the 8 subjects tried two trials on two kinds of steering assistance spring constants at each damping ratio. Therefore, there are 32 total evaluation results at each damping ratio. The objective evaluation is evaluated based on the traveling locus of the vehicle after the start of the steering assist based on the driving operation. This was designated as the evaluation item (C).
3. Result and Discussion

3.1. Subjective evaluation results
The evaluation result on the steering operability which is the evaluation item A is shown. Here, because preference is divided for each subject, we classify three subject groups with the damping ratios with the highest improvement in acceptance $\zeta = 10$, $\zeta = 15$, $\zeta = 20$ in Table 5. Three subjects answered that the damping ratio $\zeta = 10$ was the highest, and set it as the subject group $\alpha$. Similarly, two subjects who take the highest evaluation with the damping ratio $\zeta = 15$ are taken as the subject group $\beta$, three subjects with the highest evaluation with the damping ratio $\zeta = 20$ are taken as the subject group $\gamma$. Figure 4 shows the subjective evaluation result of the steering operability of the subject group $\alpha$. Similarly, Figure 5 shows the result of the subject group $\beta$, and Figure 6 shows the result of the subject group $\gamma$. Figure 7 shows the results of all 8 subjects, and also shows the results of this study and the results of the previous study. Evaluation is -2 very difficult to operate, -1 is difficult to operate, 0 is normal, +1 is easy to operate, +2 is very easy to operate. The average value of the evaluation larger is the better for the operability. As a result, the damping ratio 10 resulted in a damping ratio that was easy to operate.

From the above evaluation, since the damping ratio is preferably as small as possible from the viewpoint of safety, it is concluded that it is better to set the damping ratio to 10. In the Reference [5] in which the subject recognizes the car ahead, the result is that the evaluation is high with a damping ratio of 10. On the other hand, in the Reference [7] in which the subject does not recognize the car ahead, the result is that the evaluation is high with a damping ratio of 20. From these, we have confirmed that the damping ratio, which increases the acceptability, will change as it becomes possible to prepare for some danger by notice of the HMI, although not recognizing the car ahead.

Table 5: Subject group

| Damping ratio |  |  |  |
|---------------|---|---|---|
| 10            | 15| 20|
| Subject group | $\alpha$(3men) | $\beta$(2men) | $\gamma$(2men) |

Figure 4: Whether easy to operate the steering (group $\alpha$)
3.2. **Objective evaluation results**

As the evaluation item C, we show the result of the traveling locus of the vehicle after starting the steering assist. The results of the group of subjects with the highest evaluations of the operability evaluation in the previous section at $\zeta = 10, \zeta = 15, \zeta = 20$ are shown in Figure 8, 9, and 10, respectively. Figure 11 shows the results of all 8 subjects. The vertical axis shows the lateral displacement distance of the vehicle, and the horizontal axis shows the traveling direction distance. Normal in the graph indicates the traveling locus of the vehicle of the steering operation when the driver independently performs the same avoiding operation without assistance of the assist system.
intervention. It can be seen from the traveling locus of damping ratio $\zeta = 5, 10$ in Figure 8 that the damping ratio 5, 10 support behaves similar to normal driving, and it is a result corresponding to the subjective evaluation of the operability in Figure 4. Likewise, since the traveling locus in Figure 9 corresponds to the subjective evaluation of the operability in Figure 5 and the traveling locus in Figure 10 corresponds to the subjective evaluations in Figure 6, a traveling locus according to personal preference is taken and it is understood that the behavior near the damping ratio which was high in subjective evaluation is taken. Also, as shown in Figure 11 which is the result of all subjects, it can be seen that the traveling locus of the vehicle immediately after the normal operation start of the driver is a behavior along the damping ratio 10 and that the support of the damping ratio 10 takes a behavior close to normal operation. As the $\zeta$ becomes larger, the state of being within the danger zone becomes longer, thereby increasing the state in which the steering assistance is in operation, so that the safety decreases and it can be confirmed that the damping ratio is preferably small. Based on the subjective and objective evaluation results presented so far, it is concluded that $\zeta = 10$ is appropriate for the versatile damping ratio in this paper.

![Figure 8: Traveling locus of the vehicle (group α)](image1)

![Figure 9: Traveling locus of the vehicle (group β)](image2)
3.3. **Comparison of acceptability**

Finally, the result of the evaluation item B on the proposed steering support system is shown in Figure 12. Evaluation point -2 indicates that the support system is not considered to be good at all, -1 is not considered good, 0 does not think either, think that +1 is good, +2 thinks very good. It also shows the results of the previous research conducted without sound. As shown in Fig. 13, the evaluation value becomes the maximum with the damping ratio of 10, and the overall subjective evaluation also resulted in the agreement between the evaluation result and the damping ratio so far. Compared to the result of Reference [7] which is the case where the car ahead is overlooked and no notice is made by the sound effect, the damping ratio for improving the acceptability is smaller than when compared with the result of the advance notice given 1 second ago It was confirmed. Moreover, the literature (2) recognizing the car ahead has resulted in an increase in acceptability with a damping ratio of 10. Than these things, Since intervention support is performed in a situation where it is considered that the danger is recognized when the steering intervention support is executed, even if the damping ratio is set low, since the operation close to the normal driving operation can be performed, the receptivity can be said that it improved.
4. Conclusion
In this research, we examined how driver acceptability changes when steering assist system using impedance control is added with advance notice by HMI. As a result of the experiment, the damping ratio for improving the acceptability of the driver was reduced by introducing an advance notice sound as an auditory HMI. As the damping ratio decreases, the safety improves, so it was confirmed that the effectiveness of introducing an advance notice sound one second before.

In the future, we plan to verify the change in receptivity by changing the moment of sound effects and to investigate new support methods introducing variable viscous method.

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