Reaction Tendencies of Elderly Drivers to Various Target Paths of Proactive Steering Intervention System in Human-Machine Shared Framework

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ABSTRACT: The objective of this study was to investigate the interactions between elderly drivers and a proactive steering intervention system in a human-machine shared framework. To this end, we conducted an experiment using a driving simulator. The main focus of our analysis was on how elderly drivers react to shared driving under various conditions regarding the target paths of the system. From the result obtained for 20 elderly drivers, we confirmed three types of reaction tendencies: persistence to usual driving, persistence to newly learned driving, and autonomy abandonment.

KEY WORDS: Safety, protection of older people, driving support / proactive shared control [C1]

1. Introduction

To reduce the number of recent traffic accidents involving elderly drivers, which is a major issue in Japan, our project 1) aims to develop autonomous driving intelligence based on autonomous driving technologies, and advanced driver assistance systems (ADAS) as practical applications. To prevent traffic accidents caused by elderly drivers, we must develop ADAS that target proactive driving situations, which exist between normal and emergency driving situations. For such a development, the evaluation and improvement of acceptability are as important as the development of such technologies. Thus, in previous work, we evaluated the acceptability of proactive intervention systems, which switched the authority of vehicle control from a human driver to the machine driver 2). The results obtained by experiments confirmed that many elderly drivers did not accept the intervention of the steering system based on the switching architecture, partly because of the unintended vehicle behaviors caused by the intervention. Therefore, in this study, we focus not on a system that intervenes by switching control, but rather on a shared control intervention system. Moreover, we aimed to understand the characteristics of and potential problems pertaining to elderly drivers. Figure 1 shows the conceptual schematic representation of a human-machine shared framework with regard to a steering intervention system. In this concept, we assumed that the system conducts path planning based on risk evaluation and calculates the control value based on a certain driver model. Additionally, the system outputs an assistive torque to cooperate with a human driver. If the driver does not contribute to vehicle control, the system drives the vehicle by itself. Although this is termed “autonomous driving,” the main purpose of the system is not autonomous driving, but rather driver assistance. Thus, if a human driver does not exert sufficient control over the vehicle, the system generates an assistive torque to compensate for the driver’s inadequate operation.

The results of an existing study by Inoue et al. 3) on the steering assistance system in a human-machine shared framework revealed the usefulness of the steering shared control with direct yaw-moment control in the situation of single lane change through an experiment using a driving simulator. In another case, Hayashi et al. 4) developed an autonomous collision avoidance system using steering intervention for emergency situations. In contrast to these studies, we focus on an earlier intervention situation wherein the time-to-collision (TTC) was approximately five seconds. Figure 2 shows the conceptual schematic representation of various control strategies for a steering assistance system in a human-machine shared framework. For the short TTC range, the variety of control strategies is narrow because the driving situation is relatively simple. Moreover, for the long TTC range, the variety of control strategies is also narrow because not so many driving tasks exist. In contrast to both sides, because the variety of control strategies is wide in proactive driving situations, control strategy conflicts may occur between a human driver and the machine driver. Moreover, such conflicts may reduce the acceptability of the human driver. Therefore, this study aims to confirm the interactions between elderly drivers and the steering intervention system in a human-machine shared framework in proactive situations from a more general perspective.
2. Interactions between Human Driver and Machine Driver in Proactive Situations

2.1. Conflict of Control Strategy between Human Driver and Machine Driver

The conflict of control strategy between a human driver and the machine driver is an issue that must be considered with regard to a human-machine shared framework. Because the human driver and the machine driver simultaneously evaluate the risks of driving situations as shown in Fig. 1, their risk evaluation results may be different. In such cases, because their control strategies become different in accordance with the risk evaluations, the interference of the control operations may occur. Thus, this may decrease the acceptability for the system and driving safety. In this study, we selected the typical proactive situation of passing by a parked car as the target, because the system is assumed to assist the driver in proactive situations. In this situation, there are various vehicle control strategies. For example, some drivers conduct an early steering operation to make enough lateral space when passing by a parked vehicle, while other drivers conduct late steering operation to realize the minimum avoidance of the parked vehicle. Because the variety of vehicle control in such situations is wide, the drivers may experience a strange feeling when the different control strategy by the system is executed, as a result of risk evaluation conflicts.

As another case of conflict between the human driver and the machine driver, future ADAS based on information outside of the sensing results may cause various types of conflicts. To date, existing ADAS behave in the same manner for the same sensing results. Thus, once the users have a mental model for a certain ADAS, normal users can expect ADAS behaviors based on the results of their perception and recognition. However, presumably, future ADAS will not only use stand-alone sensor information, but also information from the network and knowledge-based information. For such ADAS, users cannot predict the behaviors of the system, although the system conducts such behaviors to assist the drivers. Thus, according to this viewpoint, we must confirm the reaction tendencies of elderly drivers with regard to the unintended behaviors of a proactive intervention system.

2.2. Feature Values for Analyzing State of Shared Control

In existing studies, the driver’s torque for the steering operation is occasionally used as an index to evaluate the driver’s behavior in a human-machine shared framework. Iwano et al. \(^\text{5}\) evaluated the operation load of steering control using the integrated value of the driver’s torque, and the feeling of steering control according to the Lissajous diagram between the driver’s torque and the yaw rate. Because their target is a relatively urgent situation, wherein pedestrians rush out from behind objects, the control strategy of a human driver is matched easily with that of the machine driver. Thus, they can investigate the state of shared control by assuming harmonization between the human driver and the machine driver.

On the contrary, because this study focused on relatively proactive situations with a wide variety of control strategies, drivers can adjust the control strategy in the range of safe driving. Additionally, for elderly drivers, the variety of driving characteristics is generally wide. Thus, in this study, we cannot assume harmonization between a human driver and the machine driver. Therefore, we should consider the driving result of shared control, rather than a shared control process, such as the driver’s torque. Based on these discussions, we focus on the trajectories to analyze the state of shared control. Specifically, we focus on two feature values: the distance between the initial avoidance point and the parked vehicle, and the width of the lateral space between the ego-vehicle and the parked vehicle. Figure 3 shows the geometric relationship of these values. The former represents the timing of the avoidance operation for a human driver and/or the machine driver. The latter represents the safety margin while passing by a parked vehicle. To discuss only the interactions regarding the avoidance operations, we focused only on the segment from the initial avoidance point to the point where the ego-vehicle is located at the side of the parked vehicle. By conducting an experiment using a driving simulator, we compared these feature values under two conditions: driving without any...
steering intervention and driving with steering intervention. In this study, we termed the former as normal driving, and the latter as shared driving.

$$r - (2)^2$$

The servomotor outputs the mixed torque of $T_a$ and $T_r$. In this way, we implemented the torque interaction system with regard to the variables. Based on the variables of vehicle motion, the assistive torque calculator and reactive torque calculator output the corresponding values: assistive torque $T_a$ and reactive torque $T_r$. The servomotor outputs the mixed torque of $T_a$ and $T_r$. In this way, we implemented the torque interaction system with regard to the shared control discussed in this study.

$$T_a = h(y_p - y_r) = h(y_{p'} - (y_c + L_p \theta)) \quad (1)$$

where $h$ denotes the steering gain, $y_p$ denotes the target lateral deviation at the preview point, $y_r$ denotes the lateral deviation at the preview point, $y_c$ denotes the center point of the vehicle, $\theta$ denotes the yawing angle, and $L_p$ denotes the preview distance, which is a constant value of 10 m in this study.

3. Implementation of Experimental System

3.1. Torque Interaction System for Shared Control

Figure 4 shows the driving simulator used in this study with the following features:

- Three front screens providing a field of view of approximately 120° from the driver’s seat.
- Steering wheel with a servomotor to reproduce the active torque.
- Speaker systems reproducing the sound of the surrounding simulated situations and the vehicle’s engine.

Figure 5 shows the system architecture around the steering wheel. Based on the steering wheel angle, which is represented as $\theta_{sw}$, a model of vehicle dynamics calculates the vehicle’s state variables. Based on the variables of the motion model, the assistive torque calculator and reactive torque calculator output the following formula: assistive torque $T_a$ and reactive torque $T_r$.

$T_{SAT} = 2\xi K_f (\beta + \frac{L_p}{r} - \frac{\theta_{sw}}{n}) \quad (3)$

where $\xi$ denotes the trail, $K_f$ denotes the cornering power of the front wheel, $\beta$ denotes the slip angle of the front wheel, $\beta$ denotes the slip angle, $L_p$ denotes the length between the center of mass and the front wheel, $V$ denotes the velocity, and $\gamma$ denotes the yaw rate. Regarding $n$, $\xi$, $K_f$, and $L_p$, we used the standard parameters for sedan type vehicles. Regarding $I$ and $C$, we adjusted them for reproducing a feeling similar to the actual vehicle by trial and error using the driving simulator.

4. Experiment

The following protocol was approved by the institutional review board for human studies of the University of Tokyo. We explained the protocol of the experiment to the participants and obtained their consent.

4.1. Participants

We recruited 20 elderly drivers (69 to 78 years old, $M = 74.6$, $SD = 2.5$) to participate in this experiment. All participants were male and held a driving license for a time period between 30 and 60 years ($M = 48.5$ years, $SD = 8.2$ years). Their average driving frequency was 4.3 days per week.
4.2. Driving Situation

Figure 7 shows a schematic representation of the driving situation. The origin of the X-axis is located at the center point of the parked vehicle, while the origin of the Y-axis is located at the center of the road, which is just on the centerline. In Japan, vehicles are driven on the left side of the road, as shown in Fig. 7. In this experiment, the velocity of the vehicle is a constant value of 30 km/h. Because we needed to simplify the discussion regarding the target path of the driver model, we set the sinusoidal target path with the two experimental parameters of D and W as shown in Fig. 7. Here, D represents the distance between the starting point of the target path and the center point of the parked vehicle, and W represents the width of the lateral space between the ego vehicle and the parked vehicle, when the ego vehicle is located at the side of the parked vehicle. Regarding the other part before and after the sinusoidal segment, the target path is located on the center of the left lane. The assistive torque is calculated based on the deviation between the target path and the preview point discussed in Section 3.2. The details of the relationship between the vehicle motion and the target path will be discussed in Section 5.2.

![Fig. 7 Schematic representation of driving situation.](image)

In this experiment, we set the three conditions of D = 80.0 m, 60.0 m, and 40.0 m. Additionally, we set the three conditions of W = 1.0 m, 1.5 m, and 2.0 m. Thus, we set nine conditions in total. Although some of these parameters represent excessively safe driving, which may not be the intended path from the viewpoint of a human driver, we set the abovementioned conditions to confirm the interactions between the human driver and the machine driver when such conditions apply.

4.3. Protocol

The following points describe the experimental protocol adopted in this study.

1. We explained the details of the system and the experiment.
2. Participants practiced driving using the driving simulator.
3. We measured six trials with normal driving and without any intervention in the target situation.
4. The participants preliminarily experienced shared driving with steering intervention by the machine driver under all nine conditions.
5. We measured six trials for shared driving under each condition.

As a result of applying the abovementioned protocol, we measured a total of 60 trials of avoiding a parked vehicle. None of the participants withdrew during the experiment as a result of motion sickness.

4.4. Instructions

In our previous study, we did not explain the objectives and detailed behaviors of the system to the drivers because we wanted to confirm the initial reactions of the elderly drivers. On the contrary, in this study, we explained the objectives and detailed behaviors of the system because we wanted to confirm the drivers’ total evaluations, which consisted of reactive and comprehensive evaluations. First, we explained to the drivers that this system was not an autonomous driving system but rather a driver assistance system based on automated driving technologies. Then, we informed the drivers that this system supports the steering operation by confirming the surrounding conditions.

Regarding the operation during the experiment, if we instructed the participants to drive in their usual manner, the drivers might have perceived the instructions as the experimental task. Similarly, if we instructed the participants to drive safely, the drivers might have perceived these instructions as the experimental task. Because we wanted to confirm the self-motivated interactions between the human driver and the machine driver under unconstrained shared driving conditions, such instructions were not appropriate. Thus, we instructed the participants to drive as they liked during the interventions.

5. Analysis

5.1. Estimation of Initial Avoidance Point

As discussed in the Section 2.2, we focused on the distance between the initial avoidance point and the parked vehicle. To calculate this distance, we had to determine the initial avoidance point. For this estimation, a numerical procedure without any arbitrariness was desirable in each case. The time series direction of the vehicle and the steering wheel angle were both candidate criteria for determining the initial avoidance point. Regarding the former, the time when the direction of the vehicle exceeded 10% of the time series direction peak value was the timing candidate of the initial avoidance point. On the contrary, regarding the latter, the time when the steering wheel angle exceeded 0 degree, was the timing candidate of the initial avoidance point.

However, the results obtained by a preliminary analysis revealed that inadequate estimations, which were calculated too early with regard to the initial avoidance point, were obtained from various driving results using both methods in this experiment. Thus, we adopted a hybrid method by integrating the former and latter methods. First, we calculated two candidate values for the initial avoidance point by using the former and latter methods. Then, we rejected the earlier timing in the final estimation result for the initial avoidance point. By using this hybrid method, we could estimate the initial avoidance point for approximately all experimental results.
5.2. Classification Concept

To confirm the types of interaction between a human driver and the machine driver, we did not have to confirm the individual driving results under each condition, but rather the trend of the shared driving results under various conditions. To confirm these trends, we had to conduct a comparison between the feature values with regard to the normal driving behavior of each participant, and the distributed feature values of shared driving under various conditions.

As discussed in Section 2.2, we focused on two feature values: the distance between the initial avoidance point and the parked car, and the lateral space width between the ego-vehicle and the parked vehicle. From the six trials under normal driving conditions, which were measured using the 3rd protocol mentioned in Section 4.3, we were able to express the normal driving characteristics. Figure 8 shows an example of the feature values for normal driving. The marker indicates their average values, while the error bars indicate their standard deviation. In this case, the participant started performing steering maneuvers for avoidance approximately 34 m before the parked vehicle, and passed by the parked vehicle with a lateral margin of approximately 1.3 m, on average. Figure 9 shows the feature value distributions under normal driving conditions for all participants.

Similarly, we can express the shared driving characteristics. Figure 10 shows an example of shared driving. The black square indicates the conditional parameters of shared driving, while the black circle indicates the autonomous driving result without any driver operation. Because we adopted the preview driver model in this study, the feature values of autonomous driving are somewhat different from those of the experimental conditions. In this case, if the driver does not operate the steering wheel under the condition of D = 80.0 and W = 2.0, the vehicle starts avoiding approximately 75 m before the parked vehicle, and passes by the parked vehicle with a lateral margin of approximately 2.0 m. On the contrary, the blue marker indicates the feature values of shared driving. In this case, the participant started performing steering maneuvers for avoidance approximately 55 m before the parked vehicle, and passed by the parked vehicle with a lateral margin of approximately 1.6 m, on average. Regarding the relationship between the positions of the black circle and the corresponding color marker, the short distance between them indicates that driver did not perform the steering operation independently of the shared driving condition. Moreover, the long distance between them indicates that the driver resisted the shared driving under that particular condition. Thus, in this case, the participant was relatively resistant to the steering intervention.

Moreover, the total distribution of the shared control results under all conditions provides an important clue with regard to the attitude of the participant toward shared driving. Figure 11 shows an example of shared driving feature values under all conditions. As can be seen in Fig. 11, the shared driving results have relatively concentrated distributions. In this case, the participant may try to drive according to his intention.

Moreover, the relationship between the normal driving result and the distributions of the shared driving results provides an additional important clue for confirming the interactions. Figure 12 shows the merged graph of Figs. 8 and 11. By confirming the relationships of these feature values, this study attempted to analyze the interactions between a human driver and the machine driver.
5.3. Classification of Interaction Types

In the following subsections, we present typical examples of interaction types. From the analysis of the results for all participants, we confirmed three types of tendencies with regard to the distribution: Persistence to Usual Driving, Persistence to Newly Learned Driving, and Autonomy Abandonment.

5.3.1. Persistence to Usual Driving

Figure 13 shows a typical example that the distribution of the shared driving results is concentrated around the normal driving result. We term this type Persistence to Usual Driving. The relatively large deviations between the shared driving result and the corresponding autonomous driving result under each condition indicate that the driver may have resisted the machine driver’s intervention. As a reference, Fig. 14 shows an example of the time series assistive torque and steering wheel angle under the condition of \( D = 80.0 \) and \( W = 2.0 \). The lateral axis represents time, and 0.0 s represents the time when the vehicle was located at the side of the parked vehicle. Between approximately -10.0 s and -7.0 s, the assistive torque became large, while the steering wheel angle was almost equal to zero. This suggests that the driver resisted the assistive torque exerted by the machine driver. Additionally, another characteristic is that the shared driving results are distributed toward the normal driving result. Thus, this driver may intend to drive as usual, even under shared driving conditions.

5.3.2. Persistence to Newly Learned Driving

Figure 15 shows a typical example of a concentrated distribution with regard to the shared driving results. We term this type Persistence to Newly Learned Driving. The relatively large deviations between the shared driving result and the result corresponding to autonomous driving, under each condition, exhibit tendencies that are similar to the tendencies observed in the case of Persistence to Usual Driving. However, in contrast to the case of Persistence to Usual Driving, the shared driving results are not concentrated around the normal driving result. Because the large deviations between the autonomous driving and the shared driving results were confirmed, the shared driving results are based on the driver’s intention. Thus, the driver may learn new driving styles from the preliminary experience in the 4th protocol mentioned in Section 4.3. In that case, the participants classified into this type may be flexible in terms of interacting with the shared control.

5.3.3. Autonomy Abandonment

Figure 16 shows a typical example of a non-concentrated distribution. We term this type Autonomy Abandonment. In contrast to the other two cases, the shared control results are not concentrated. Additionally, the deviations between the shared driving result and the corresponding result of autonomous driving under each condition were relatively small. Moreover, Fig. 17 shows the time series assistive torque and steering wheel angle. As can be seen in Fig. 17, the time series assistive torque was relatively small. These results demonstrate the possibility of the
participant abandoning driving autonomy and passing over the authority of vehicle control to the machine driver.

Fig. 16 Typical result of autonomy abandonment.

Fig. 17 Time series assistive torque and steering wheel angle of autonomy abandonment.

5.4. Classification of All Participants

To confirm the number of participants classified into each type, we had to apply a numerical procedure and classify the participants into each case without any arbitrariness. To develop a classification method that represented the characteristics of each type mentioned in Section 5.3, we defined four area types with regard to the graph of the feature values, as follows. Figure 18 shows an example for each area.

- Area AD,W: Area AD,W is defined as a rectangle with a width of 40 m, and a height of 1.0 m. The center point of the rectangle is the point of the experimental condition (D, W). Because we set nine conditions, there existed nine areas for area A, such as area A80,2.0. These areas were constant for all participants.
- Area B: Area B is defined as the minimum rectangle including all points of the experimental conditions. This area was constant for all participants.
- Area C: Area C is defined as the minimum rectangle including the average shared driving feature values under all conditions. This area varied for each participant.
- Area D: Area D is defined as the minimum rectangle including the average feature values with error bars indicating the standard deviation of normal driving without any intervention. This area also varied for each participant.

Based on the abovementioned area definitions, we developed the classification flow for the participant types, as shown in Fig. 19. The flow conditions were as follows:

- Condition 1: All average feature values under each condition were located within the corresponding area A80,2.0.
- Condition 2: The normal driving feature values were located outside of area B.
- Condition 3: Areas C and D have a common segment.
- Condition 4: The feature values of normal driving were located within area C.

As a result of the classification based on the abovementioned flow, the number of each type was as follows: 12 participants for the type of Persistence to Usual Driving, four participants for the type of Persistence to Newly Learned Driving, and four participants for the type of Autonomy Abandonment. Although the number of participants classified into the Persistence to Usual Driving type was larger than half, the number of participants in this experiment was only 20. Thus, we believe that these proportions were limited by the experimental results.

6. Discussions

Because the ultimate objective of our study was to develop ADAS in a human-machine shared framework, we should discuss the adaptability to the shared control and determine potential problems regarding the classification into each type. With regard to the type of Persistence to Usual Driving, because the drivers resisted the steering intervention by the machine driver, the shared control may not work well as the ADAS. Additionally, because the drivers tended to drive as usual, the safety under the shared control condition does not depend on the safety of the system, but rather on the safety of the driver’s usual driving behavior. Thus,
for drivers whose usual driving is not safe, adequate instructions and advice for dealing with the ADAS are necessary to ensure safe driving. Moreover, if the drivers do not cooperate with the shared control, even when the driving situation becomes dangerous, much more compulsive approaches will be needed. Although the enlargement of the maximum value of assistive torque is one such compulsive approach, the drivers may still resist the intervention by exerting a much larger amount of driver operation torque. In this case, because the load of the steering operation becomes large, it is not a good solution as an assistive system. Thus, we believe that a handover system is necessary, whereby the authority of vehicle control is removed from a human driver in progressively dangerous situations.

With regard to the type of Persistence to Newly Learned Driving, the drivers were flexible in interacting with the shared control, contrary to the case of the Persistence to Usual Driving type. Although we investigated shared driving under various conditions, we believe that the dependence of driver attitude on the system under all conditions is not always a good relationship between the human driver and the machine driver. A key point in the context of a human-machine shared framework is the compensation when the behavior of the human driver, or that of the machine driver, is inadequate. From this perspective, the change of driving strategy, which might be learned from the shared driving, indicates the possibility that they can deal with the shared control in a good relationship.

Regarding the Autonomy Abandonment type, although the drivers did not resist the steering intervention, they did not exhibit any independence regarding vehicle control. Thus, dangerous driving situations may occur if the behaviors of the machine driver are inadequate, owing to the failure of surrounding recognition. Because this is a type of overreliance in safety systems, adequate instructions and advice for the autonomy of driving are necessary for dealing with the shared control. In this regard, we think that overreliance does not occur for the participants classified into the types of Persistence to Usual Driving and Persistence to Newly Learned Driving.

7. Conclusions

To reduce the amount of traffic accidents caused by elderly drivers, we focused on a proactive steering intervention system in a human-machine shared framework. To investigate the reaction tendencies of elderly drivers, we conducted an experiment using a driving simulator. Moreover, we analyzed the driving results by conducting comparisons between the feature values under normal driving condition and the feature values under shared driving conditions. As a result, we confirmed the following points:

- We confirmed three types of reaction tendencies: Persistence to Usual Driving, Persistence to Newly Learned Driving, and Autonomy Abandonment.
- Regarding the types of Persistence to Usual Driving and Autonomy Abandonment, careful instructions are necessary to use the shared control as a driver assistance system.
- Regarding the type of Persistence to Usual Driving, a handover system is necessary in progressively dangerous situations.

However, further investigation is needed. Because this study was conducted as a first step toward investigating interactions with the shared control, the driving situation investigated in the experiment did not include any actual dangerous situations. Thus, situations that are actually dangerous must be investigated in future work. Additionally, because this study was conducted using a driving simulator, the correspondence of the considered scenario to reality was limited. Thus, further investigations using an actual vehicle are also necessary. Moreover, because this study focused only on elderly drivers, experiments with younger drivers must be conducted to investigate general trends. Furthermore, we must also investigate the relationship between the driver types and their individual characteristics to understand the decision making mechanism why they chose such maneuvering strategy. Finally, we must investigate and evaluate the handover system for the type of Persistence to Usual Driving. These topics will be investigated in future work.

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