Investigation of the Advanced Rider-Assistance System of a Personal Electric Vehicle Using Personal Space

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Abstract—Recently, personal mobility vehicles for individual use have attracted tremendous attention as eco-friendly transportation for short-distance trips in urban areas. In this paper, we investigate the advanced rider-assistance system of a four-wheeled personal electric vehicle that supports the rider in recognizing the psychological strain of surrounding pedestrians using the concept of personal space. The proposed system detects nearby pedestrians using range sensors, informs the rider about the invasion of the vehicle via a micro-vibration motor, and cooperates with the rider in avoiding the pedestrian. The experiment was conducted under different conditions of pedestrian densities, and questionnaires were used to evaluate participants’ feelings such as discomfort and fear. The findings revealed that the effectiveness of the proposed assistance system was confirmed.

Index Terms—advanced rider-assistance system, psychological factor, personal electric vehicle, personal space, vibration motor

I. INTRODUCTION

These days, in the context of exhausting fossil fuel and environmental problems, many researchers worldwide have tried to find solutions for transportation, such as developing electric vehicles and hybrid electric vehicles or proposing alternative fuels for vehicles. For short-distance trips, personal mobility vehicles (PMVs), which are suitable for individual use, have been recently offered. Such vehicles are environmentally-friendly, compact, and convenient to use in pedestrian areas such as walkways, pedestrian streets, and shopping malls [1]. As a result, many kinds of PMVs have been recently developed, especially two-wheeled inverted pendulum vehicles [2]–[3]. However, when PMVs are allowed to be used in pedestrian flows, it is essential to consider the psychological factors of nearby pedestrians toward PMVs. There has been growing interest in the safety issues and psychological effects of PMVs on surrounding pedestrians when PMVs move in a flow of pedestrians. Sayed et al. investigated automated safety diagnosis of vehicle-bicycle interactions using computer vision analysis [4]. Nishiuchi et al. analyzed the behaviors of Segway, focusing on safety distance for pedestrians and the gaze of riders [5]. Xu et al. investigated head injuries of self-balancing scooter’s riders using the virtual vehicle-scooter crash scenarios [6]. Nakagawa et al. analyzed avoidance difficulty levels following the type of PMV [7] and examined the effect of the size of a PMV on a pedestrian [8]. Pham et al. evaluated the assistance system for a two-wheeled vehicle using personal space (PS) [9] and estimated a semi-active assistance system of PMV’s driver [10]. Intelligent wheelchairs that can assist the riders and avoid collisions and with pedestrians have been proposed [11]–[12]. Dias et al. analyzed a safe avoidance system for pedestrians in PMVs and mixed pedestrian traffic [13] and investigated pedestrians’ danger perception toward PMVs interacting with them in shared space [14].

Generally, a two-wheeled PMV is compact and suitable to use in pedestrian areas; however, this is an unstable and nonlinear system; therefore, for the vehicle to balance by itself, control approaches need to be implemented by using a gyroscope and accelerometer sensors [15]–[16]. In recent years, many researchers have proposed diverse control strategies for such PMVs. Ren et al. examined a self-tuning proportional-integral-derivative control strategy based on a deduced model for implementing a motion control system that stabilizes a two-wheeled vehicle and follows desired motion commands [17]. Jung and Kim proposed a control approach for a mobile inverted pendulum using a neural network control combined with a proportional-integral-derivative controller [18].

Furthermore, driving two-wheeled vehicles is not always an easy task, and it may be difficult for riders to maintain balance while driving the vehicle. Meanwhile, four-wheeled PMVs like Scooter Q3-Chariot [19], which can easily maintain balance, have been introduced in recent years. Nevertheless, such vehicles use a mechanical steering system and are not compact to operate in pedestrian areas. Therefore, this study develops a compact four-wheeled personal electric vehicle (PEV) that uses electric energy, providing green, convenient,
and safe mobility in urban areas. Furthermore, to enhance the safety and comfort of surrounding pedestrians in the presence of the proposed vehicle, a driving assistance system considering pedestrians’ psychological factors was investigated.

The remaining sections are structured as follows. In Section II, an advanced rider-assistance system for a four-wheeled PEV is proposed. Section III describes experiments on personal space and participants’ feelings of discomfort and avoidance difficulty, experimental analysis results. Finally, Section IV provides conclusions and future work.

II. DEVELOPMENT OF ADVANCED RIDER-ASSISTANCE SYSTEM FOR THE FOUR-WHEELED PEV

Previous studies examined the simulation of personal mobility vehicles based on PS using invasion ratio and crossing time as evaluation indexes [20]–[21]. In addition, a semi-active assistance system was evaluated by riders as the vehicle operated at speeds of 4 km/h and 6 km/h in accordance with low and high steering angle gains [10]. In this study, we develop an advanced rider-assistance system for the four-wheeled PEV considering the psychological factors of surrounding pedestrians. The assistance system detects a nearby pedestrian using range sensors and informs the rider about the invasion of the vehicle using a vibrator. Fig. 1 describes the procedure of the proposed system.

Fig. 1. Procedure of advanced rider-assistance system.

Fig. 2 illustrates the control system configuration of the vehicle, which includes three main parts: sensors (inputs), actuators (outputs), and an electronic controller that is responsible for executing the control algorithm for the vehicle.

![Control block diagram of the PEV with an advanced rider-assistance system](image)

For vehicle motion control, the data from the speed control potentiometer, wheel speed sensors, steering angle sensor, and control switches are fed to the controller. The controller then processes, calculates, and generates signals to control two motors appropriate to the operational mode of the vehicle. For controlling the assistance system, ultrasonic sensors are employed to determine the PS of pedestrians, and a micro-vibration motor and an LED are used to inform the rider about the invasion of the PEV.

The appearance of a PEV prototype is shown in Figure 3. The prototype has rear-wheel drive using two electric motors, and the front wheels were equipped with Omni-directional wheels, which can roll freely in two directions, helping the PEV turn smoothly. Moreover, the designed vehicle can move forward and backward via actuating control switch 11, turn via turning handlebar 10, and change the velocity via adjusting velocity rotary switch 9. The designed vehicle is controlled by an electronic controller 3, put under platform 4, as shown in Fig. 3.

The electronic controller for the vehicle consists of an LPC 1768 microcontroller, with a 32-bit ARM Cortex M3 processor and a diversity of input/output interfaces, including pulse-width modulation, an analog-to-digital converter, and an inter-integrated circuit. Moreover, three ultrasonic XL-MaxSonar-EZ1 range finders were employed to determine the front and side distances between the PEV and nearby pedestrians. Additionally, a light-emitting diode (LED) and a micro-vibration motor were mounted on the handle of the PEV to inform the rider about the invasion of the PEV. The coin-type vibration motor was attached to the handlebar, which can generate vibration amplitude large enough so that the driver can recognize PS invasion status [22]. The vibration amplitude of the motor was controlled in
accordance with the level of PS invasion of the vehicle. Increasing the PS invasion increases the vibration amplitude, helping the PEV rider recognize the invasion level of the PEV. Table I shows the parameter of the vibration motor.

Table I. Parameters of vibration motor for experiment

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body diameter (mm)</td>
<td>10</td>
</tr>
<tr>
<td>Body thickness (mm)</td>
<td>3</td>
</tr>
<tr>
<td>Voltage range (V)</td>
<td>1.6–3.5</td>
</tr>
<tr>
<td>Rated vibration speed (rpm)</td>
<td>12500 ± 2500</td>
</tr>
<tr>
<td>Rated current (mA)</td>
<td>65</td>
</tr>
</tbody>
</table>

Furthermore, the advanced rider-assistance system cooperates with the rider in avoiding the PS of a pedestrian when the PS invasion arises to get out of the PS of a pedestrian faster. In this study, the steering is performed by controlling the difference between the angular speeds of the left and right rear wheels. When the rider of the PEV applies a steering angle on the handlebar, the controller acts immediately on the two motors, reducing the speed of the inner wheel and increasing the speed of the outer wheel. Steering angle gain \( K_s \) is defined as the ratio between the turning angular velocity of the vehicle \( (d\phi_V/dt) \) and turning angle of the handle \( (\phi_H) \), which is expressed as

\[
K_s = \frac{d\phi_V}{d\phi_H}.
\]

The steering angle gain increases with an increase in the invasion ratio of pedestrians, as shown in Fig. 4. This helps the PEV evade the PS of a pedestrian faster while invading the PS of a pedestrian.

Figure 3. PEV with advanced driver-assistance system

A. Experimental Measurement of PSs

In previous studies, Nakagawa et al. measured the static and dynamic PSs of pedestrians encountering PMVs [23]. Pham et al. investigated the PS of a pedestrian and a two-wheeled inverted pendulum vehicle [24]. In this study, we continued determining the PSs of a pedestrian and a four-wheeled electric vehicle.

The experiment was conducted under the condition that a four-wheeled PEV encountered 15 subjects one by one. The pedestrians consisted of 15 people (sex: 13 male/2 female, average age: 24.7 years old, range: 22–31 years old), and safety in the experiments was explained to participants. In this experiment, we assumed that the PEV travels in a pedestrian area at a low velocity of about 4 km/h (the same pedestrian velocity).

Figure 4. Steering angle gain according to invasion ratio.

where \( K_s^{\text{with}} \) and \( K_s^{\text{without}} \) are steering angle gains of the vehicle with and without assistance system, respectively.

III. Experiment and Results

A. Experimental Measurement of PSs

The experiment was conducted under the condition that a four-wheeled PEV encountered 15 subjects one by one. The pedestrians consisted of 15 people (sex: 13 male/2 female, average age: 24.7 years old, range: 22–31 years old), and safety in the experiments was explained to participants. In this experiment, we assumed that the PEV travels in a pedestrian area at a low velocity of about 4 km/h (the same pedestrian velocity).

Figure 5. Measurement of pedestrian’s PS.
The experimental area was over 10 m long in the traveling direction and wide enough to allow avoidance. In this experiment, we used two cameras to measure the PSs of a pedestrian and the vehicle. The PS of a pedestrian and the PEV were distances that caused discomfort when a pedestrian and a PMV were traveling toward each other, as described in Figs. 5 and 6.

After conducting the experiment, by analyzing the data from the cameras, the PSs of a pedestrian and the PEV were determined. Table II shows the experimental results of the PSs of a pedestrian and the PEV $(N = 15)$, which were used as input parameters for the advanced rider-assistance system for the vehicle. The results reveal that the PSs of a pedestrian were larger than those of the PEV, respectively. This means that the discomfort level generated by the PEV rider was higher than that caused by the pedestrian when a pedestrian traveled toward the PEV. Besides, there was a statistically significant difference between the PS of a pedestrian and the PS of the PEV (Wilcoxon test $N = 15$, $p < 0.05$).

### TABLE II. EXPERIMENTAL RESULTS ON PS OF PEDESTRIAN AND PEV (MEAN AND STANDARD DEVIATION)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Pedestrian</th>
<th>PEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front PS (m)</td>
<td>4.8 (0.84)</td>
<td>4.4 (0.72)</td>
</tr>
<tr>
<td>Side PS (m)</td>
<td>0.82 (0.18)</td>
<td>0.75 (0.24)</td>
</tr>
</tbody>
</table>

#### B. Experiment on Participants’ Feelings

The previous study [10] evaluated the effectiveness of a semi-active assistance system by experiment when the vehicle operated at speeds of 4 km/h and 6 km/h in accordance with low steering gain ($K_{S1}$) and high steering gain ($K_{S2}$). The results revealed that the effectiveness of the semi-active assistance system had been confirmed by the driver. However, the experiment was conducted in the condition that the vehicle encountered pedestrians one by one.

To confirm the effectiveness of the proposed assistance system in more realistic scenarios, we continue conducting experiments in the measurement of feelings of pedestrians and PEV riders with the advanced rider-assistance system. In the experiment, we assumed that the PEV travels at low velocity in a pedestrian area of a Japanese road pedestrian area, and we constructed an experimental scenarios model with a PEV traveling toward ten pedestrians for different pedestrian densities of 0.1, 0.2, and 0.3 people/m$^2$. The experiment was conducted at Osaka Prefecture University under the condition that the PEV encountered a flow of pedestrians. The experimental area was 20 m long in the traveling direction and wide enough to allow the PMV to avoid pedestrians, as shown in Fig. 7. This figure is admitted to use by the experimental participants.

Fig. 8 describes the layout of the experiment, such as the positions of pedestrians and the PEV. The experimental area has length $l$ and width $w$. The pedestrian density in the experiment was varied following the values of $l$ and $w$, as shown in Table III.

### TABLE III. PEDESTRIAN DENSITY ACCORDING TO THE SIZE OF EXPERIMENTAL AREA

<table>
<thead>
<tr>
<th>Density (people/m$^2$)</th>
<th>$l$ (m)</th>
<th>$w$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>0.2</td>
<td>12.5</td>
<td>4</td>
</tr>
<tr>
<td>0.3</td>
<td>10</td>
<td>3</td>
</tr>
</tbody>
</table>

During the experiment, the PEV riders avoided pedestrians when recognizing the invasion via the advanced driver-assistance system. Meanwhile, the pedestrians traveled in straight lines from their initial positions toward the PEV and evaded the PEV when they felt uncomfortable or fearful. After conducting the experiment, participants were asked to complete the questionnaire sheets in two different modes of the vehicle operating with and without the assistance system, as shown in Table IV.
### TABLE IV. QUESTIONNAIRES

<table>
<thead>
<tr>
<th>No.</th>
<th>Participants</th>
<th>Questions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1</td>
<td>Riders</td>
<td>How uncomfortable do you feel when driving the PEV in the pedestrian flow? (1-comfortable, 2-slightly uncomfortable, 3-somewhat uncomfortable, 4-mostly uncomfortable, and 5-very uncomfortable)</td>
</tr>
<tr>
<td>Q2</td>
<td>Riders</td>
<td>How difficult did you feel when avoiding pedestrians? (1-normal, 2-slightly difficult, 3-somewhat difficult, 4-mostly difficult, and 5-very difficult)</td>
</tr>
<tr>
<td>Q3</td>
<td>Pedestrians</td>
<td>How uncomfortable do you feel when sharing the space with a PEV? (1-comfortable, 2-slightly uncomfortable, 3-somewhat uncomfortable, 4-mostly uncomfortable, and 5-very uncomfortable)</td>
</tr>
<tr>
<td>Q4</td>
<td>Pedestrians</td>
<td>How fearful do you feel when sharing the space with a PEV? (1-normal, 2-slightly fearful, 3-somewhat fearful, 4-mostly fearful, and 5-very fearful)</td>
</tr>
</tbody>
</table>

### C. Rider’s Evaluation

The evaluation results for the feelings of discomfort and avoidance difficulty by five riders (mean and standard deviation) are shown in Table V. The results show that the rider’s levels of discomfort and pedestrian avoidance difficulty when the PEV equipped with the assistance system were lower than those for the case of the PEV without the assistance system. This could be because the assistance system helps the rider recognize invading the PS of nearby pedestrians and assists the rider in avoiding the pedestrians.

### TABLE V. EXPERIMENTAL RESULTS EVALUATED BY RIDERS

<table>
<thead>
<tr>
<th>Density</th>
<th>Feeling</th>
<th>Discomfort level</th>
<th>Avoidance difficulty</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Without assistance system</td>
<td>With assistance system</td>
</tr>
<tr>
<td>0.1</td>
<td>1.3 (0.48)</td>
<td>1.1 (0.32)</td>
<td>1.3 (0.48)</td>
</tr>
<tr>
<td>0.2</td>
<td>2.2 (0.42)</td>
<td>1.6 (0.52)</td>
<td>2.2 (0.42)</td>
</tr>
<tr>
<td>0.3</td>
<td>3.2 (0.42)</td>
<td>2.7 (0.67)</td>
<td>3.2 (0.63)</td>
</tr>
</tbody>
</table>

### D. Pedestrians’ Evaluation

Table VI presents the results for the levels of discomfort and fear felt by ten pedestrians toward the PEV when operating with and without the assistance system. The pedestrians reported that their levels of discomfort and fear felt toward the PEV with the assistance system were lower than those felt toward the PEV without the assistance system. This may be because the assistance system helps the PEV avoid the PS of a pedestrian faster while invading the PS of a pedestrian.

### TABLE VI. EXPERIMENTAL RESULTS EVALUATED BY PEDESTRIANS

<table>
<thead>
<tr>
<th>Density</th>
<th>Feeling</th>
<th>Discomfort level</th>
<th>Fear level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Without assistance system</td>
<td>With assistance system</td>
</tr>
<tr>
<td>0.1</td>
<td>1.42 (0.67)</td>
<td>1.33 (0.65)</td>
<td>1.08 (0.29)</td>
</tr>
<tr>
<td>0.2</td>
<td>2.17 (0.83)</td>
<td>1.75 (0.97)</td>
<td>1.33 (0.49)</td>
</tr>
<tr>
<td>0.3</td>
<td>2.58 (1.00)</td>
<td>2.33 (0.78)</td>
<td>1.75 (0.75)</td>
</tr>
</tbody>
</table>

### IV. CONCLUSIONS

In this paper, we have investigated an advanced rider-assistance system for a four-wheeled PEV considering the psychological factors of pedestrians. The following findings were obtained.

- The PSs of a pedestrian and the PEV were determined by experiment. It was found that the PSs of the PEV were smaller than those of a pedestrian. The data PSs were used as inputs of the proposed assistance system.
- The proposed assistance system was evaluated by the riders and pedestrians under different conditions of pedestrian density. Experimental results reveal that the assistance system was effective at the pedestrian densities of 0.1, 0.2, and 0.3 people/m².

As future works, we will optimize the controller of the driving assistance system that will improve the efficiency of the proposed system. Furthermore, we will consider conducting experiments in higher pedestrian densities and actual scenarios.

### CONFLICT OF INTEREST

No potential conflict of interest was reported by the authors.

### AUTHOR CONTRIBUTIONS

Chihiro Nakagawa, Atsuhiko Shintani, and Tomohiro Ito were in charge of conceptualization, methodology, formal analysis, writing—review and editing, project administration. Pham Quoc Thai is the corresponding author of this research work. He was in charge of conceptual generation, software, validation, formal analysis, writing—original draft preparation, and editing. All authors have read and agreed to the published version of the manuscript.

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