Modeling and simulation of multiple personal mobility vehicles in pedestrian flows using personal space

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Received: January 29, 2015; Accepted: June 3, 2015; Published: November 6, 2015

Abstract. Personal mobility vehicles (PMVs), such as an inverted-pendulum vehicle, have been attracting attention as next-generation vehicles for individual use. However, when PMVs travel in pedestrian flows, it is necessary to consider the safety and comfort of pedestrians. This paper investigated a simulation model considering the interaction between multiple PMVs and pedestrians, and analyzed the effects of PMVs in pedestrian flows using the concept of personal space. Furthermore, we proposed an assistance system for PMVs in order to ensure comfort for pedestrians in the presence of PMVs. The simulation results revealed that the avoidance angle and the velocity of PMVs significantly affected the invasion of pedestrians’ PSs, and the effectiveness of the assistance system was clearly confirmed.

Keywords: Assistance system, Pedestrians, Personal mobility vehicles, Personal space, Simulation

1. Introduction

Personal mobility vehicles (PMVs) are expected as new individual transportation vehicles that are environmentally-friendly, compact, and convenient. Recently, many studies related to PMVs have been proposed [1-4], and a variety of PMVs have been introduced, such as Segway [5], Winglet [6], yooPT [7], and U3-X [8]. However, a question has been raised about how to reduce pedestrians’ discomfort and fear toward PMVs when PMVs operate in pedestrian flows. There has been considerable interest in the psychological factors in accordance with PMVs or robots and pedestrians. Butler et al. investigated the interactions between people and mobile personal robots by focusing on the psychological effects of robot behavior.
patterns during task performance [9]. Walters et al. analyzed the interaction between people and a robot based on the hypothesis of human social interactions [10]. In recent studies, we considered psychological factors relating to PMVs and pedestrians; e.g., we analyzed discomfort level of pedestrians according to the type of PMV [11], measured personal spaces (PSs) for pedestrians encountering PMVs [12], and evaluated effects of a PMV on multiple pedestrians using PS under different conditions of pedestrian density [13].

In this study, we develop a model of multiple PMVs traveling in pedestrian flows and analyze the effects of multiple PMVs on pedestrians under different conditions of velocity and avoidance angle of PMVs. Moreover, an assistance system for PMVs has been proposed in order to enhance pedestrians’ feelings of safety and comfortableness.

The remainder of this paper is organized as follows. Section 2 outlines the proposed methodology including a description of PS, the concept of assistance system for PMVs, analysis of behavior models of the PMV, an evaluation index, and simulation conditions. Section 3 describes an experiment on the measurement of PS. Simulation results are presented and discussed in Section 4. Finally, Section 5 provides conclusions and discusses future work.

2. Methodology

2.1. Fundamentals of PS

The notion of PS was proposed by Edward T. Hall in 1966. PS is the space in which invasion by others induces a psychological strain. Most people may value their PS and feel uncomfortable when their PS is encroached [14]. The front PS \( (a) \) is the head-on distance between two heads when one starts avoiding the other whereas the side PS \( (b) \) is the lateral distance between two heads when one begins evading the other. The form of PS is set as an egg shape with a longer length in the traveling direction [12, 15, 16], as illustrated in Fig. 1.

![Figure 1: Personal space of a pedestrian](image-url)
2.2. Concept of assistance system for PMVs

To enhance comfort and safety for pedestrians in the presence of PMVs, we proposed an assistance system for PMVs using the concept of PS. The assistance system is described in Fig. 2, in which a PMV detects surrounding pedestrians using range sensors and calculates the PS of a pedestrian from state quantities such as distance and velocity. When the PMV invades the PS of a pedestrian, the assistance system will inform the driver about the invasion using a vibrator, a sound signal, or a light signal. The driver of the PMV then avoids the pedestrian; otherwise, the PMV will automatically decelerate and evade the pedestrian.

![Figure 2: Procedure of the assistance system for a PMV](image)

2.3. Simulation model

In this study, a simulation model of multiple PMVs in pedestrian flows is built based on the concept of PS. Fig. 3 shows the calculation model of multiple PMVs traveling toward a flow of pedestrians. To recognize an invasion of PS, the positions of PMVs and pedestrians need to be determined. The positions of PMVs and pedestrians can be expressed as the following coordinates:

\[
\begin{align*}
x_i(t + dt) &= x_i(t) + v_i(t) \cos \phi_i(t) dt, \\
y_i(t + dt) &= y_i(t) + v_i(t) \sin \phi_i(t) dt, \\
x_j(t + dt) &= x_j(t) + v_j(t) \cos \phi_j(t) dt,
\end{align*}
\]

(1) \(\qquad\) (2) \(\qquad\) (3)
where \( x_i(t), y_i(t), x_k(t), \) and \( y_k(t) \) are \( x \) and \( y \) coordinates of PMV \( i \) and pedestrian \( k \), respectively, and \( x_i(t+dt), y_i(t+dt), x_k(t+dt), \) and \( y_k(t+dt) \) are \( x \) and \( y \) coordinates of the PMV and pedestrian at time \( t + dt \) whereas \( v_i(t), v_k(t), \varphi_i(t), \) and \( \varphi_k(t) \) are velocities and moving direction angles of the PMV and pedestrian at time \( t \).

The PS of PMV \( i \) \( (S_{PSi}(t)) \) can be calculated as

\[
S_{PSi}(t) = (x, y) \begin{cases} 
\frac{(x - x_i(t))^2 + (y - y_i(t))^2}{a_i^2(t)} & 1 \text{ if } x < x_i(t), \\
\frac{(x - x_i(t))^2 + (y - y_i(t))^2}{b_i^2(t)} & 1 \text{ if } x > x_i(t). 
\end{cases}
\]

The PS of pedestrian \( k \) \( (S_{PSk}(t)) \) can be determined as

\[
S_{PSk}(t) = (x, y) \begin{cases} 
\frac{(x - x_k(t))^2 + (y - y_k(t))^2}{a_k^2(t)} & 1 \text{ if } x < x_k(t), \\
\frac{(x - x_k(t))^2 + (y - y_k(t))^2}{b_k^2(t)} & 1 \text{ if } x > x_k(t). 
\end{cases}
\]

In the above equations, \( a_i(t), b_i(t), a_k(t), \) and \( b_k(t) \) are the front PS and side PS of the PMV and pedestrian, respectively. In this study, we used the dimensions of the PS obtained in the experiment presented in Section 3. The PS of PMV \( i \) is invaded by pedestrian \( k \) when \( (x_i(t), y_i(t)) \ S_{PSi}(t) \), the PS of pedestrian \( k \) is invaded by PMV \( i \) when \( (x_k(t), y_k(t)) \ S_{PSk}(t) \).

To analyze the effects of multiple PMVs on nearby pedestrians, a behavior model of PMVs in pedestrian flows is proposed. Moreover, to clarify the effectiveness of the assistance system for PMVs, we examined the model of PMVs with and without the assistance system.
2.3.1. Behavior model of PMVs without assistance system

The behaviors of PMVs without assistance system only depend on the PSs of PMVs. Fig. 4 is a flowchart of the behavior model of two PMVs A and B without assistance system. Initially, the PMVs and pedestrians travel in straight lines from their initial positions, and when pedestrians enter the visual field of PMVs’ drivers, the drivers judge whether pedestrians are within the PSs of PMVs. If pedestrians invade the PSs of PMVs (determined by using (5)), then the process of avoidance begins; otherwise, PMVs continue traveling in a straight line. During the process of avoidance, the avoidance direction and avoidance angle of the PMVs depend on positions and distances between the PMVs and invaders. The avoidance angle is the maximum turning angle of a PMV when evading pedestrians.

Figure 4: Flowchart of the behavior model of multiple PMVs without assistance system

Figure 5: Behavior of multiple PMVs without the assistance system
Fig. 5 shows that PMV A without the assistance system begins avoidance when a pedestrian enters the PS of the PMV; meanwhile, PMV A has already invaded the PS of the pedestrian. This may make the pedestrians feel fearful and uncomfortable.

### 2.3.2. Behavior model of PMVs with assistance system

To reduce the levels of fear and discomfort felt by pedestrians, the behavior model of PMVs with the assistance system was proposed. Fig. 6 illustrates a flowchart of the behavior model of PMVs with the assistance system, in which PMVs decelerate and avoid nearby pedestrians as pedestrians invade the PSs of PMVs (determined by (5)) or as PMVs enter the PSs of pedestrians (determined by (6)).

![Flowchart of the behavior model of multiple PMVs with the assistance system](image)

**Figure 6: Flowchart of the behavior model of multiple PMVs with the assistance system**

Fig. 7 illustrates the behaviors of the PMVs equipped with the assistance system, in which the PSs of PMVs and pedestrians are considered. PMV A equipped with the assistance system begins decelerating and avoiding a pedestrian when entering the PS of a pedestrian even though the pedestrian is outside the PS of the PMVs. This may result in pedestrians feeling safer and more comfortable when sharing space with PMVs.
2.4. Evaluation index

To evaluate the effects of PMVs on pedestrians, the invasion ratio and crossing time are proposed [15, 17]. The invasion ratio is a physical index that expresses the extent to which the PS of a pedestrian is invaded, as depicted in Fig. 8. The invasion ratio \( I \) is expressed as

\[
I = \frac{l_a}{l_b} \times 100\%
\]

where \( l_a \) is the length of the PS, and \( l_b \) is the length of invasion.

The crossing time \( t \) is the time from when a PMV invades the PS of a pedestrian to when the PMV leaves the PS of the pedestrian. The average of the invasion ratio during the crossing time is referred to as the average invasion ratio \( I_{av} \), which is expressed as

\[
I_{av} = \frac{\int_0^t I(t) \, dt}{t}
\]

where \( I(t) \) is the instantaneous value of the invasion ratio. The average invasion ratio for \( N \) pedestrians \( (I_{av}) \) is determined as
\[ I_{av} = \frac{1}{N} \sum_{k=1}^{N} I_{avk}, \quad (9) \]

where \( I_{avk} \) is the average invasion ratio for pedestrian \( k \).

**2.5. Simulation conditions**

In the simulation, multiple PMVs travel toward a flow of pedestrians. The effects of the PMVs on pedestrians were investigated under different conditions of PMVs’ avoidance angle and velocity. In this study, the drivers of PMVs were supposed to be friends together; therefore, the distance between two PMVs could be small (0.25 m). Furthermore, because PMVs have not yet been allowed to be used on public roads in Japan, as a first step, it is realistic to show the comfort of pedestrians encountering the vehicles traveling at low velocity. Therefore, we also assumed that PMVs travel at low speeds in a pedestrian flow. Data for pedestrians and the PMVs given in Table 1 and 2 were taken from previous studies [12, 15]. Simulation parameters of PSs obtained in the experiment are described in Section 3.

**Table 1: Parameter of pedestrians**

| Parameter                  | Value |
|----------------------------|-------|
| Shoulder width [m]         | 0.45  |
| Body thickness [m]         | 0.25  |
| Head diameter [m]          | 0.2   |
| Pedestrians’ velocity [km/h] | 4    |
| Pedestrian density [people/m^2] | 0.25 |
| Pedestrian’s visual viewing angle [°] | 180 |

**Table 2: Parameter of PMVs**

| Parameter                  | Value |
|----------------------------|-------|
| PMV width [m]              | 0.45  |
| PMV’s initial velocity [km/h] | 2-6  |
| Avoidance angle [°]        | 15-30 |
| PMV’s acceleration [m/s^2] | 0.3   |
| Distance between PMVs [m]  | 0.25  |
| Driver’s visual viewing angle [°] | 180 |
3. Experimental measurement of PS

To determine the effect of PMV’s velocity on the PS of a pedestrian, an experiment was carried out. In this experiment, we used an inverted-pendulum vehicle called yooPT that moves forward and backward via the movement of the gravity center of the driver, and turns via turning of the joystick of the handle. Fig. 9 shows the PMV for the experiment.

In this study, we assumed that the PMV travels in a pedestrian area of a Japanese road at a speed lower than 6 km/h. The experiment was conducted under the condition that the PMV encountered 15 subjects one by one. The experimental area was over 10 m long in the traveling direction and wide enough to allow avoidance. To measure the front PS and side PS, we used two video cameras. An overhead camera recorded the front PS while a camera placed on the ground recorded the side PS. Fig. 10 is a photograph of the experiment on PS.
By analyzing the data of avoidance behaviors of the PMV and a pedestrian, and experimental results from [12] and [13], the PSs of the PMV and a pedestrian were determined. Table 3 gives the results for the PS of a PMV encountering a pedestrian at a velocity of 4 km/h.

Table 3: Experimental results on the PS of the PMV

| Parameter                  | Value |
|----------------------------|-------|
| PMV’s front PS [m]         | 4.9   |
| PMV’s side PS [m]          | 0.7   |

The PS of a pedestrian was determined in the condition that a pedestrian evaded the PMV and for the velocity of the PMV traveling at 0 to 6 km/h. The results of the PS of a pedestrian obtained are indicated in Figs 11 and 12.

Figure 11: Front PS of a pedestrian according to PMV’s velocity

\[ a = -1.005v^2 + 1.4529v + 0.8763 \]

Figure 12: Side PS of a pedestrian according to PMV’s velocity

\[ b = 0.029v + 0.7364 \]

where \( a \) and \( b \) are the front PS and side PS of a pedestrian, respectively, and \( v \) is the velocity of the PMV.
4. Simulation results

The simulation was conducted under the condition that multiple PMVs traveled toward a pedestrian flow with a pedestrian density of 0.25 people/m² at initial position of PMV A ((x, y) = (0, 0.35 m)) and of PMV B ((x, y) = (0, –0.35 m)). Moreover, the simulation was analyzed under different conditions of the avoidance angle and the velocity of the PMVs.

Figure 13: Behaviors of multiple PMVs without and with the assistance system in a pedestrian flow at five different positions of PMVs and pedestrians (corresponding to five times 1.1s, 3.1s, 5.8s, 7.3s, and 10.3s). The asterisk (*) indicates the reduction of pedestrians’ PSs due to decreasing the velocity of PMVs.
Fig. 13 compares the simulation results of the behaviors of multiple PMVs without the assistance system (Fig. 13a) and with the assistance system (Fig. 13b) at five different times ($t = 1.1, 3.1, 5.8, 7.3, \text{ and } 10.3 \text{s}$) with PMVs’ initial velocity of 4 km/h. The simulation results reveal that when the PMVs were equipped with the assistance system, pedestrians’ PSs reduced because the PMVs decelerated in recognition of their invasion of the pedestrians’ PSs. Pedestrians may thus feel safer and more comfortable in the presence of PMVs.

4.1. Influence of PMVs’ avoidance angle

The simulation was conducted for PMVs’ avoidance angles of 15, 20, 25, and 30 degrees. Fig. 14 shows the simulation results for the average invasion ratio of PMV A and PMV B according to avoidance angle, respectively, whereas Fig. 15 depicts the results for the crossing time according to avoidance angle. Furthermore, the results are compared for the PMVs with and without the assistance system.

The simulation results reveal that an increase in the avoidance angle led to lesser invasion of the pedestrians’ PSs by the PMVs and shorter crossing time because the PMVs find it easier to avoid pedestrians at a larger avoidance angle. Furthermore, the PMVs equipped with the assistance system had the average invasion ratio and the crossing time that were lower than that for the PMVs without the assistance system. Additionally, the results for PMV A were higher than that for PMV B because pedestrian density on the side of PMV A was higher than that on the side of PMV B.
4.2. Influence of PMVs’ velocity

The simulation was conducted under the condition that PMVs traveled toward a pedestrian flow at velocities of 2, 4, and 6 km/h. Figs. 16 and 17 show the simulation results for the average invasion ratio and the crossing time of PMV A and PMV B, respectively, according to PMVs’ velocity. The results are also compared for the PMVs with and without the assistance system.

The simulation results reveal that the average invasion ratio increased with increasing the velocity of PMVs. However, the crossing time increased with an increase in PMVs’ velocity from 2 km/h to 4 km/h and decreased as the velocity increased from 4 km/h to 6 km/h. This decrease may be because when the velocity of PMVs increased from 4 km/h to 6 km/h, the effect of decreasing the crossing time was greater than that of increasing pedestrians’ PS. More-
over, the PMVs equipped with the assistance system had the evaluation indexes lower than those for the PMVs without the assistance system.

5. Conclusion and future work

In this paper, a model of multiple PMVs traveling in a pedestrian flow using personal space has been proposed. In addition, the assistance system for PMVs was investigated, and the effectiveness of the assistance system was analyzed under different conditions of the avoidance angle and the velocity of PMVs.

The simulation results suggest that the invasion ratio and the crossing time of pedestrians were significantly affected by the avoidance angle and the velocity of PMVs. As the avoidance angle of the PMVs was small or as the velocity of the PMVs increased, the invasion ratio and the crossing time increased. Furthermore, the effectiveness of the assistance system was clearly confirmed in the simulation. The PMVs equipped with the assistance system have invasion ratio and crossing time lower than those of the PMVs without assistance system. Pedestrians may thus feel safer and more comfortable because PMVs reduce the velocity during the crossing.

The present findings encourage the development of PMVs by considering psychological effects on pedestrians in terms of their feelings of safety and comfort. Further work will concentrate on developing prototype PMVs with the assistance system, and then conducting experiments using such PMVs and analyzing the driver’s reaction in order to verify the validity of our proposed system.
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