Passenger's Comfort Recognition during Autonomous Navigation of Personal Mobility Vehicles in Crowded Pedestrian Spaces

Yosuke Isono, Hiroshi Yoshitake and Motoki Shino

Department of Human and Engineered Environmental Studies, Graduate School of Frontier Sciences, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba, Japan

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Abstract: The development of autonomous navigation systems for personal mobility vehicles is underway to support mobility in large-scale facilities such as airports and shopping malls where pedestrians coexist. One of the required functions of autonomous navigation is comfort, such as not causing anxiety to the passengers. The purpose of this study is to clarify the characteristics of passenger's comfort recognition, that is, how the passenger feels comfortable depending on the behavior of the surrounding pedestrians and the vehicle when the personal mobility vehicle moves autonomously in a crowded environment. An experiment was conducted to obtain subjective assessment of passenger comfort using a VR simulator. By focusing on situation awareness as a process affecting passenger's comfort recognition, the influence of situation awareness on passenger's comfort recognition was analyzed and the characteristics of passenger's comfort recognition were discussed.

1 INTRODUCTION

The population of older adults in Japan is increasing year after year, and both the number of people with physical disabilities and the number of people with dementia are increasing. To support the mobility of older adults, there is a growing need not only for outdoor mobility support using public transportation and shared-ride services, but also for indoor mobility support after arriving at a destination due to the increasing scale of facilities. Currently, most mobility support services at airports and other largescale facilities rely on manual labor (e.g., a facility staff pushing a wheelchair). However, the development of autonomous navigation systems of personal mobility vehicles (PMVs) such as electric wheelchairs is in progress and it is expected to reduce labor shortages and labor costs (Leaman and La, 2017).

A PMV drives through the pedestrian space, which is a mixed space with pedestrians and PMVs. Autonomous navigation systems of PMVs are required to be able to carry the passenger to a designated destination, be safe and free from collisions with static objects and pedestrians, and be comfortable without causing anxiety to the passenger. In our research, we aim to realize an autonomous navigation system of a PMV that is comfortable for passengers and can be used in large-scale facilities (e.g., airports and shopping malls).

Research on passenger comfort in autonomous navigation of PMVs can be roughly divided into two types: research focusing on ride comfort and research focusing on a sense of security. As for the former type, International Organization for Standardization has established evaluation criteria of acceleration applied to seated human beings (ISO, 1997), and there are researches on methods generating smooth paths using vehicle acceleration and jerk as indicators (Bevilacqua et al., 2016; Yoshitake et al., 2020). In terms of the latter type, the concept of personal space, which is the space in which people feel uncomfortable with the presence of others, has been studied (Hall, 1966). Personal space is perceived as an elliptical area with a long axis in front of oneself. Pham et al. investigated the discomfort of PMV passengers by focusing on the degree of invasion of others into the personal space (Pham et al., 2015). As methods for generating comfortable paths, there are researches focusing on static environments where there are no pedestrians (Morales et al., 2013; Morales et al., 2018) and dynamic environments when passing by pedestrians (Morales et al., 2017). In our research, the acceleration and jerk of the PMV are kept to a level that does not impair the ride comfort of passengers, and the sense of security is focused on as passenger comfort.

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The comfortable autonomous navigation methods avoiding obstacles and passing by pedestrians proposed in previous research assumes situations where the PMV can take enough distance from obstacles and pedestrians. However, in large-scale facilities such as airports and shopping malls, many pedestrians exist at the same time. When the environment is crowded (i.e., with pedestrians above a certain density), pedestrians will inevitably invade the personal space of the PMV passenger. It is known that passengers feel uncomfortable when pedestrians invade their personal space. However, characteristics of comfort recognition in a crowded environment where the surrounding situation changes from time to time and the personal space being inevitably invaded have not been discussed. By investigating these characteristics of passenger's comfort recognition, it is expected to lead to novel autonomous navigation methods that reduce discomfort while allowing pedestrians to invade the passenger's personal space in a crowded environment. Therefore, the purpose of this study is to clarify the characteristics of passenger's comfort recognition, that is, how the passenger feels comfortable depending on the behavior of the surrounding pedestrians and the PMV when the PMV moves autonomously in a crowded environment. To obtain fundamental data as an exploratory study aimed at finding factors that constitute passengers' comfort recognition, the experiment was conducted on young participants following previous research(Gwak et al., 2021), although older people use PMVs more than healthy people. This study deals with a mobility scooter as a form of the PMV.

2 PROCESS OF PASSENGER'S COMFORT RECOGNITION

The driving behavior process of a PMV driver in a crowded environment was focused on to consider the passenger's comfort recognition process during autonomous navigation in a similar environment. In a crowded environment, the driver understands the state of pedestrians from their behavior and posture and selects his/her action according to the state. This method can be thought of as selecting a less uncomfortable action even in situations where pedestrians' invasion into the personal space is unavoidable. This process of recognition and judgment in the driver behavior matches with the situation awareness model of Endsley (Endsley, 1995). In Endsley's situation awareness model, information processing consists of situation awareness, decision, and performance of actions. Moreover, the process of situation awareness

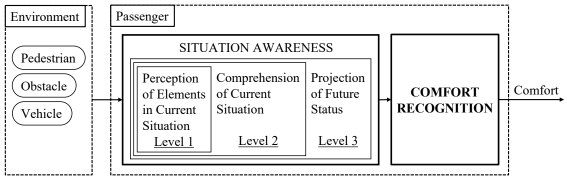


Figure 1: Process of passenger's comfort recognition based on the situation awareness.

consists of the following three stages:

- Level 1: Perception of the Elements in the Current Situation.
- Level 2: Comprehension of the Current Situation.
- Level 3: Projection of the Future Status.

This indicates that in recognizing the environment, it is necessary not only to perceive the shapes and positions of objects (Level 1), but also to understand what their positional relationships and movements mean to oneself (Level 2), and to predict what the future status may be from the current situation (Level 3). In addition, recognition is affected by task- and system-side factors such as the characteristics of the vehicle or system being used, as well as personal factors such as memory, goals, and expectations that depend on the personal ability and experience.

When focusing on autonomous navigation, the stage of performance of actions that existed during manual driving is no longer present. However, the passenger can be considered to perceive the surrounding environment and recognize comfort (i.e., feel comfortable or uncomfortable) as a result of the situation awareness stage in place of the decision stage. Therefore, the passenger's comfort recognition process in this study is expressed with the situation awareness stage, as shown in Figure 1. In other words, the passenger recognizes comfort based on the results of situation awareness using elements of the surrounding environment such as pedestrians, obstacles, and the autonomous PMV as input information.

To understand the characteristics of comfort recognition, the relationships between situation awareness and passenger comfort are examined in this study. First, an experiment is conducted to obtain passenger's subjective assessment of comfort when the PMV moves autonomously in the target crowded environment. The effect of the Current Situation and the Future Status in situation awareness on comfort recognition is analyzed using the obtained data. Finally, the characteristics of passenger's comfort recognition are discussed considering the analysis results.

3 PASSENGER COMFORT EVALUATION EXPERIMENT

The purpose of this experiment is to evaluate how passengers recognize comfort during autonomous navigation of PMVs in the target crowded environment. The requirement of the experiment is to be able to evaluate the passenger's comfort quantitatively to enable an analysis of the relationship between passenger comfort and situation awareness.

The experiment was done with a virtual reality (VR) simulator. Scenes with different autonomous movement of a PMV and pedestrians' behavior in the target crowded environment are simulated in a VR environment and presented to the participants using a head-mounted display (HMD). In addition, the passenger's degree of discomfort is obtained along the time axis. A VR simulator was adopted in this experiment for two reasons. First, the simulator can control the behavior of the PMV and pedestrians easily and repeatedly, where this is difficult in the real world. Second, the simulator is free from actual collisions where there is a possibility of collisions between the autonomous PMV and pedestrians in the real world.

3.1 Scene Conditions

To present scenes with different behavior of the autonomous PMV and pedestrians to participants in a VR environment, the behavior of both the autonomous PMV and pedestrians in a crowded environment was simulated numerically. The environment is a 6-meter-wide aisle in a shopping mall. There are 30 pedestrians approaching the PMV and the pedestrian density of the environment is approximately 0.125 $/\mathrm{m}^2$. The pedestrians follow the Social Force Model (Zanlungo et al., 2011), and the initial position, target speed, and destination are set individually. The autonomous navigation method of the PMV in the simulation is based on the Dynamic Window Approach (Fox et al., 1997), which is a widely used method in the field of robotics. The method also takes into account the movement of surrounding pedestrians to perform avoidance actions (Guan et al., 2018). The numerical simulation was conducted assuming that pedestrians within the measurement range could be recognized accurately and that there was no skidding of the PMV. Under these conditions, 16 scenes with different behaviors of pedestrians and the autonomous PMV were simulated.

Figure 2: Image inside head-mounted display.

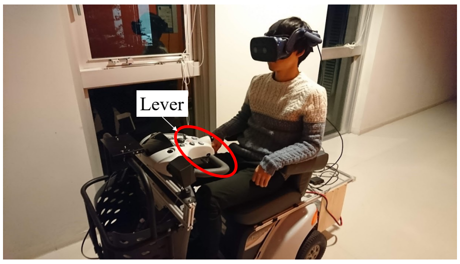


Figure 3: Experiment setup.

3.2 Equipment and Methods

The created scenes were simulated in a VR environment using Unity and presented to the participants using VIVE Pro Eye (HTC Corporation). A sample view of the VR environment created based on the simulation is shown in Figure 2. As for the experimental environment, the participants sat in a real mobility scooter and wore an HMD, as shown in Figure 3. The mobility scooter's motor was rotated according to the speed of the PMV inside the VR environment without moving the actual PMV to increase the sense of realism. As a method of obtaining passenger comfort quantitatively and continuosly, the degree of discomfort was obtained in real time as an analog scale instead of a Likert scale. The lever on the handle indicated by the red circle in Figure 3 was used. The participants were asked to input their degree of discomfort with the lever on an analog scale from 0 to 1, where 1 is the most uncomfortable moment.

The participants first experienced all 16 scenes without evaluating their discomfort. This process was set to enable the participants to become familiar with the equipment and the behavior of pedestrians and the autonomous PMV. In addition, this process let the participants to define their own standard of discomfort during autonomous navigation. The discomfort was then obtained using the method described above. Each of the 16 scenes was played in a random order to remove the order effects.

3.3 Participants

The experiment was conducted on healthy young participants to ensure fundamental data as an exploratory study. Ten males in their 20s (23.0 ± 0.77 years old) participated in this experiment. The experimental procedures and details of the experiment were explained to the participants before the experiment, and informed consent was obtained. The experiment was conducted under the approval of the Ethics Committee of the University of Tokyo.

4 EFFECTS OF CURRENT SITUATION ON COMFORT RECOGNITION

In this chapter, the effect of the Current Situation, which corresponds to Level 1 and 2 of situation awareness in Endsley’s model, on the passenger’s comfort recognition is analyzed. Here, it is said in the previous study (Hall, 1966) that people feel uncomfortable when others invade their personal space. This phenomenon corresponds to the Current Situation. Therefore, the invasion of surrounding pedestrians into the personal space of the PMV passenger is used as a cue for the analysis. First, the relationship between the sections where the passenger feels uncomfortable and the sections where the personal space is invaded is investigated. Second, the relationship between the degree of discomfort and the degree of invasion is investigated.

4.1 Analysis of Uncomfortable Sections

4.1.1 Method

When identifying an uncomfortable section, it can be considered that the discomfort of a certain section is higher when more participants input discomfort at the section. Therefore, the number of participants who input discomfort was counted along the time axis for each scene. The section where there is discomfort input of two or more participants is defined as the ”uncomfortable section.”

The size of the vehicle and the personal space is shown in Table 1. The size of the personal space was calculated by considering the difference in the size of the vehicle dealt with in the previous study (Pham et al., 2015). The personal space has an oval shape, as shown in Figure 4, with the passenger’s head at the center, an ellipse with the major axis l_f in the front and the minor axis l_s in the side, and a circle with the radius l_s in the rear.

Table 1: Size of vehicle and personal space.

Vehicle length	1.19 m
Vehicle width	0.65 m
Front personal space (l_f)	5.62 m
Side personal space (l_s)	0.80 m

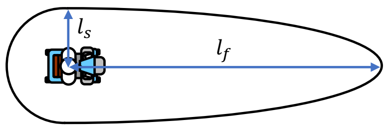


Figure 4: Size of personal space.

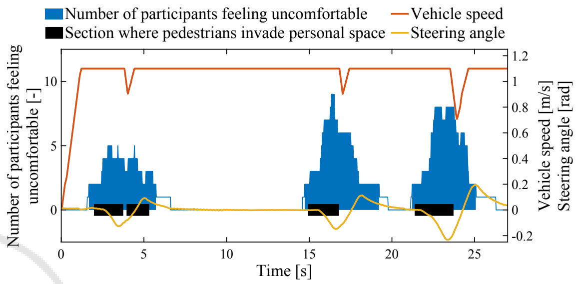


Figure 5: Changes in the number of participants feeling uncomfortable (Scene No. 3).

4.1.2 Result

Figure 5 shows the number of participants inputting discomfort in a certain scene, along with the vehicle speed and steering angle at that time. In Figure 5, the section where pedestrians invade the personal space is filled in black. From Figure 5, it can be seen that the timing of the discomfort input of the participants is greatly influenced by the presence of pedestrians invading the personal space of PMV passengers. The uncomfortable section is the area filled in blue in Figure 5. Among the 16 scenes, there were 46 uncomfortable sections, and 41 of these overlapped with sections where pedestrians were invading the personal space. As for the remaining five sections, there were no pedestrians invading the personal space. However, there were pedestrians near the personal space. From the results, it was found that the presence of pedestrians invading the personal space has a significant impact on the passenger’s discomfort. This is in line with the results of previous studies.

4.2 Analysis of Degree of Discomfort

4.2.1 Method

The results of the previous section indicated that the presence of pedestrians invading the personal space has a significant impact on the passenger's discomfort. In this section, the quantitative relationship between the invasion of pedestrians into the personal space and the passenger's discomfort is analyzed.

As a quantitative index for pedestrian's invasion into the personal space of a PMV passenger, the invasion ratio, which has been used in the previous study (Pham et al., 2015), is adopted. The invasion ratio is a physical index that expresses the extent to which the personal space of a pedestrian is invaded, as shown in Figure 6. The invasion ratio I is expressed as

$$I = \frac{l_b}{l_a}. \qquad (1)$$

Next, the discomfort of the passengers is quantified. As mentioned in the previous section, it is considered that the discomfort is higher when more participants input discomfort at the same time. In addition, the larger the input value of discomfort is, the more the participants feel uncomfortable. Figure 7 shows the frequency distribution of discomfort input values on an analog scale among all 16 scenes for two different participants. As it can be seen from the figures, there was a large individual difference in the input characteristics of discomfort among the participants. Thus, it is inappropriate to use the input values of discomfort on the analog scale as a quantification index of discomfort directly. Therefore, the input value of discomfort was corrected as follows according to the input characteristics of each individual:

$$q' = \begin{cases} 0 & (q = 0), \\ 0.5 & (0 < q \leq q_{median}), \\ 1 & (q_{median} < q \leq 1), \end{cases} \qquad (2)$$

where q is the input discomfort value, q' is the corrected discomfort value, and q_{median} is the median of the frequency distribution of all input values for each individual. The value $\bar{q'}$, which is the average value of all the participants, is used as a quantitative index of passenger discomfort along the time axis. The quantitative time trends of pedestrian invasion ratio and passenger discomfort are shown in Figure 8 using the above indices.

In analyzing the relationship of passenger discomfort in response to pedestrian invasion ratio, this relationship was investigated by focusing on the uncomfortable sections. As a measure of pedestrian invasion into the personal space during a certain section, the

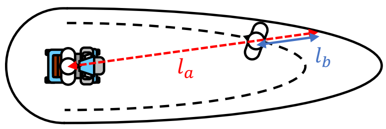
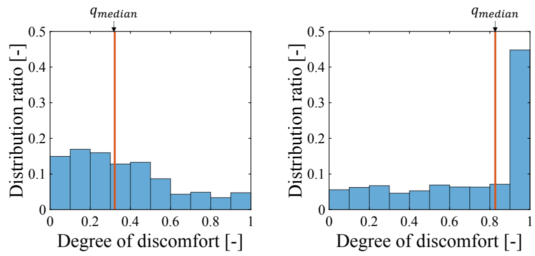


Figure 6: Definition of invasion ratio.



(a) Participant ID 1. (b) Participant ID 2.

Figure 7: Examples of input characteristics of degree of discomfort.

time integration of the invasion ratio for all the pedestrians who invaded the personal space was adopted. $I_{invasion\_ratio}$ represents the invasion of pedestrians into the personal space for a certain section which is expressed as

$$I_{invasion\_ratio} = \sum_{j \in S} \int_{I_j(t)>0} I_j(t)dt, \qquad (3)$$

where S is the set of pedestrians who invaded the personal space in the section of interest, and $I_j(t)$ is the instantaneous value of the invasion ratio of pedestrian j. As an index of passenger's discomfort during a certain section, the time integration of the passenger's discomfort $\bar{q'}$ was adopted. The time integration was adopted because this discomfort is considered to be stronger when the input value is larger and the input time is longer. $I_{passenger\_discomfort}$ represents the passenger's discomfort for a certain section which is expressed as

$$I_{passenger\_discomfort} = \int_{t_1}^{t_2} \bar{q'}(t)dt, \qquad (4)$$

where t_1 and t_2 are the start and end times of the uncomfortable section.

4.2.2 Result

Figure 9 shows the relationship between the pedestrian invasion into the personal space and the passenger's discomfort for the 41 uncomfortable sections. The coefficient of determination for the linear approximation was near 0.6. This indicates that the invasion ratio of pedestrians into the personal space is an important factor in evaluating passenger's discomfort quantitatively.

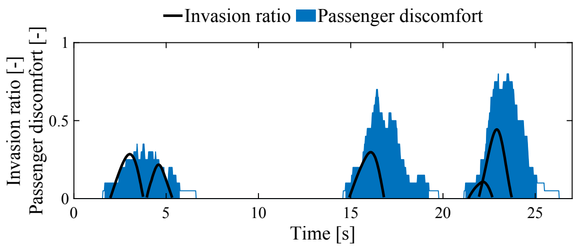


Figure 8: Trends in invasion ratio and passenger discomfort (Scene No. 3).

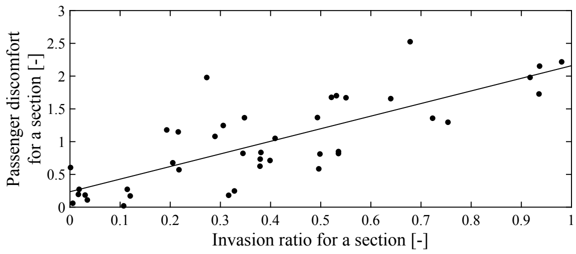


Figure 9: Correlation between invasion ratio and passenger discomfort for each section.

4.2.3 Discussion

The results in the previous section showed that there was a strong relationship between the invasion ratio of pedestrians and passenger's discomfort. However, there were sections that showed a rather weak relationship, such as the sections apart from the linear approximation line. These sections were further analyzed and two factors affecting passenger's discomfort were identified. The first factor was that the vehicle was approaching the wall. There were two sections where the PMV was approaching the wall, and these sections were relatively uncomfortable, as shown in Figure 10. This result was inconsistent with the previous study (Morales et al., 2013), where people felt uncomfortable when the distance from the wall was close. The second factor was that the pedestrian invades the personal space within 5.0 s after the scene starts. Fourteen sections, which were around the start of the scene, were relatively comfortable situations, as shown in Figure 10. Immediately after the scene starts, both the vehicle and the pedestrian begin to accelerate from a stopping state. It is assumed that the sensitivity of the passenger's discomfort against pedestrian invasion was low before reaching a steady-state, and this led to the evaluation of a relatively comfortable section.

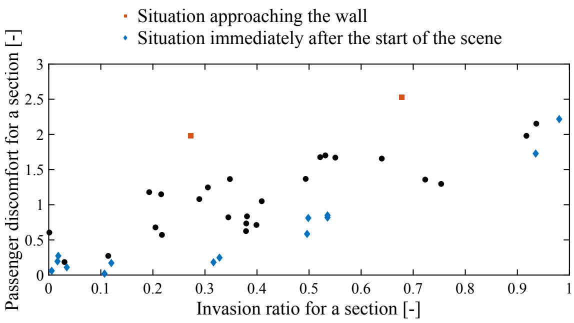


Figure 10: Sections that showed a rather weak relationship.

5 EFFECTS OF FUTURE STATUS ON COMFORT RECOGNITION

In this chapter, the effect of the Future Status, which corresponds to Level 3 of situation awareness in Endsley's model, on the passenger's comfort recognition is analyzed. The results of the previous chapter showed that the invasion into the personal space has a great impact on comfort recognition as a factor of the Current Situation. In this chapter, the status before the pedestrian's invasion into the personal space (pre-invasion status) is focused on as the Future Status, and the effect on the passenger's comfort recognition is analyzed. First, pre-invasion statuses that affect comfort recognition are extracted by comparing the pre-invasion statuses among the relatively comfortable and uncomfortable sections. Second, the effect of the extracted pre-invasion status is examined quantitively.

5.1 Comparison of Pre-invasion Statuses

5.1.1 Method

To extract the pre-invasion status that affects passenger's comfort recognition, the relationship between the invasion ratio and the passenger discomfort, as discussed in the previous chapter, was analyzed by focusing on the scenes that became relatively uncomfortable and relatively comfortable in response to the invasion ratio. As a method of classifying relatively uncomfortable and relatively comfortable sections, the 25 uncomfortable sections, which were not influenced by the wall or the start of the scene, are linearly approximated and the sections that fall outside of the 50% prediction intervals were defined as relatively uncomfortable or relatively comfortable sections. The characteristics of the pre-invasion status of these sections are analyzed qualitatively.

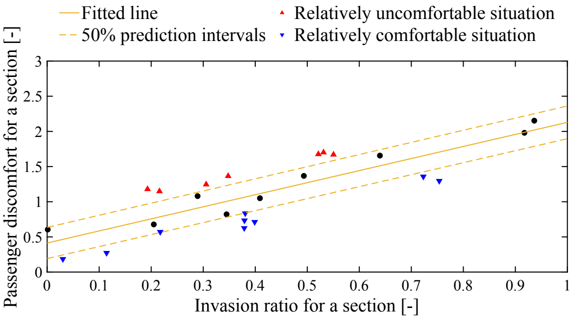


Figure 11: Classification into relatively uncomfortable and relatively comfortable situations.

5.1.2 Result

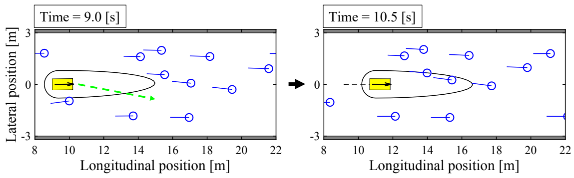
Figure 11 shows the relationship between the invasion ratio and the passenger discomfort for the 25 sections, excluding the 16 sections where factors other than pedestrians were involved, and shows the linear approximation line and the 50% prediction intervals. Comparison of two classified section groups showed that for the sections classified as relatively uncomfortable, the autonomous PMVs did not avoid the pedestrians even though there was enough space to avoid them. Figure 12-(a) shows an example of the situation where the vehicle could have avoided the pedestrian but did not do so. In contrast, Figure 12-(b) shows an example of a situation where the vehicle could not avoid the pedestrian in the first place. From this, the pre-invasion status that a vehicle did not avoid pedestrians although it could was extracted as a status that leads to passenger discomfort. The difference between the current status of the vehicle, which is not taking any avoidance action, and the passenger's expectation, which is that the vehicle would take an avoidance action, is considered to have an effect on comfort recognition.

5.2 Examination of Effects of Pre-invasion Status on Comfort Recognition

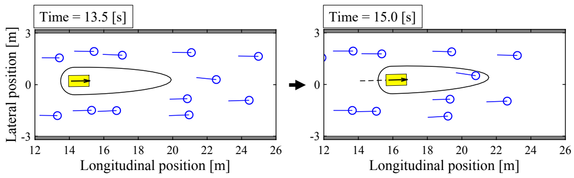
In this section, the effect of the pre-invasion status extracted in the previous section on passenger discomfort is examined quantitatively.

5.2.1 Method

To examine the effect of the pre-invasion status, two factors are quantified: whether the vehicle is taking an avoidance action and whether the vehicle can avoid the pedestrians.



(a) Situation where the vehicle could have avoided the pedestrian but did not take any avoidance action (Scene No. 1).



(b) Situation where the vehicle could not avoid the pedestrian in the first place (Scene No. 10).

Figure 12: Comparison of the ability to avoid pedestrians.

First, whether the vehicle is taking avoidance actions or not is quantified. A vehicle is considered to be taking an avoidance action if it is decelerating or turning. Thus, the criteria for deceleration action are set as follows:

$$v \leq 0.9 v_{max} \quad \wedge \quad \frac{\Delta v}{\Delta t} \leq 0, \tag{5}$$

where v is the vehicle speed and v_{max} is the maximum vehicle speed. The criteria for turning action are set as follows:

$$|\alpha| \geq 2 \quad \vee \quad \left|\frac{\Delta\alpha}{\Delta t}\right| \geq 2.5, \tag{6}$$

where α [degree] is the steering angle. A vehicle is considered to be taking avoidance action when it satisfies (5) or (6).

Next, whether the vehicle can avoid the pedestrians or not is quantified. A vehicle is considered to be able to avoid pedestrians if it can travel for a longer time without approaching pedestrians or walls by steering the vehicle. Therefore, the focus is on the time duration the vehicle can continue traveling without approaching pedestrians or walls, both when the vehicle continues traveling at the current steering angle and when the steering angle is changed from that angle. Whether or not the vehicle can continue to travel for several seconds is a future phenomenon, and thus requires a prediction process. The following describes the method of quantification based on the prediction process. As a prediction process in this study, the vehicle motion is assumed to follow the vehicle model and the pedestrian position is assumed to have a probabilistic distribution. The probability distribution of the pedestrian is a bivariate normal distribution centered on the position of constant velocity

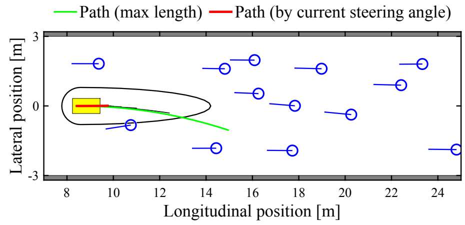


Figure 13: Difference in the length of the path that can be drawn by different steering angles (Scene No. 1).

linear motion, and the variance is calculated from the actual position error in the scenes. First, the probability p_n of any pedestrian invading the personal space of the vehicle after n steps is determined using the method of previous research (Lambert et al., 2008). Here, pedestrians are limited to a range of 15 m from the vehicle, and the time per step is $\Delta t = 0.5$ s. In this case, the probability q_n that the vehicle can continue traveling in n steps without approaching pedestrians is expressed as

$$q_n = \left(\prod_{i=1}^{n} (1 - p_i) \right) p_{n+1}. \tag{7}$$

At this time, the expected value T of the time that the vehicle can continue driving without approaching pedestrians is expressed as

$$T = \Delta t \sum_{i} i q_i. \tag{8}$$

The above process is applied to the case where the vehicle continues to travel at the current steering angle and to the cases where the steering angle is changed from the current angle. The steering angle is varied in increments of 0.5° over a range of ±3°. Figure 13 shows an example of the difference in the length of the path that the vehicle can continue to travel without approaching pedestrians or walls. If the vehicle continues to move at the current steering angle, a pedestrian will invade the personal space a few seconds ahead. However, if the steering angle is turned to the right, a longer path can be drawn without the pedestrian invading the personal space.

Using the above indices, Figure 14 shows the sections where the vehicle is not taking any avoidance action and the sections where the vehicle is not taking any avoidance action despite being able to avoid the pedestrian, respectively. Here, the criterion for being able to avoid pedestrians is defined as the case where changing the steering angle from the current value increases the travel time T by 1.3 s or more. In Figure 14, the section surrounded by the blue dotted line indicates the section until the pedestrian invades the personal space for the uncomfortable section.

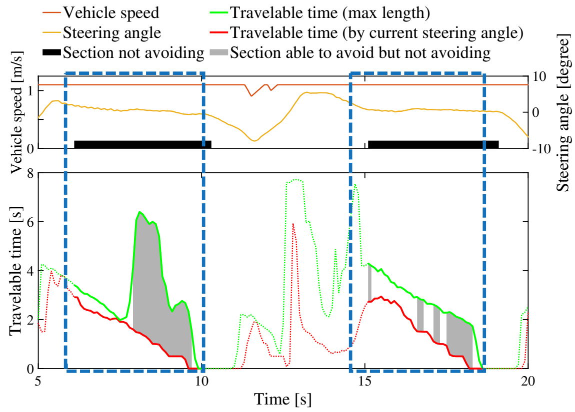


Figure 14: Sections where the vehicle is not avoiding and the sections where the vehicle is able to avoid but not avoiding (Scene No. 1).

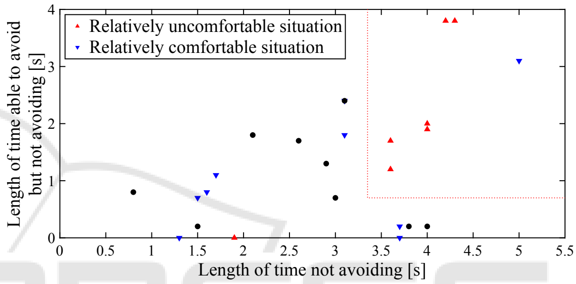


Figure 15: Classification based on the length of time that the vehicle is not avoiding and the length of time that the vehicle is able to avoid but not avoiding.

5.2.2 Result

Based on the above process, Figure 15 shows the length of time that the vehicle is not avoiding on the horizontal axis and the length of time that the vehicle is able to avoid but not avoiding on the vertical axis for the 25 uncomfortable sections. In Figure 15, if the horizontal axis is greater than 3.35 s and the vertical axis is greater than 0.7 s, six sections can be classified correctly (*recall* = 0.85) among the relatively uncomfortable sections. Conversely, one section is misclassified (*precision* = 0.85). Therefore, by focusing on whether the vehicle is taking avoidance actions and whether the vehicle can avoid the pedestrians before invading the personal space, it is possible to explain the scenes that became relatively uncomfortable for the invasion ratio. On the other hand, in response to the pre-invasion status that a vehicle did not avoid pedestrians although it could and it leads to passenger discomfort, it was found that there is a condition that the status continues for a certain amount of time.

5.2.3 Discussion

The first condition on the horizontal axis (the length of time that the vehicle is not avoiding is more than 3.35 s) suggests that when there is a pedestrian who may invade the personal space in the future, if the vehicle does not take avoidance action for a certain time period and the status continues, the passenger's awareness toward the pedestrian will become stronger. As a result, the sensitivity of discomfort to invasion into the personal space is expected to increase. The second condition on the vertical axis (the length of time that the vehicle is able to avoid but not avoiding is more than 0.7 s) suggests that when there is a threat of invading the personal space for a long time, if the vehicle does not take appropriate avoidance action when avoidance is possible, it will lead to stronger discomfort. On the other hand, when it is known that avoidance is not possible, the discomfort can be suppressed to a reasonable level.

6 CHARACTERISTICS OF PASSENGER'S COMFORT RECOGNITION

The characteristics of passenger's comfort recognition are summarized based on the previous discussions. As described in Chapter 2, situation awareness was focused on as a process that affects passenger's comfort recognition in this study. As a result of analyzing the effect of the Current Situation in situation awareness on comfort recognition, the invasion ratio of pedestrians into the personal space had a significant impact on the passenger's discomfort, similar to previous research results. This suggests that recognition of the current state of the surrounding environment is included, and that one of the outputs of the current state recognition, the invasion ratio into the personal space, is an input for the comfort recognition. Next, as a result of analyzing the effect of the Future Status in situation awareness on comfort recognition, the discomfort becomes stronger when a PMV does not take any actions even though it can avoid approaching pedestrians that may invade the personal space in the near future, and when this status continues for a certain time period. This suggests that passengers have some expectations of the PMV's behavior, and that when these expectations differ from the actual behavior, it leads to stronger discomfort. Moreover, the difference between actual and expected behavior does not immediately strengthen discomfort, but it does after a certain time. The expected behavior of an autonomous PMV in a crowded environment is to take appropriate action after determining where it can travel to avoid approaching pedestrians. From this process, it is considered that the prediction of pedestrian behavior and the judgment of avoidability based on the prediction are included as elements of the model. The difference between the expectations generated by this process and the actual behavior appears as an increase in the weighting factor of discomfort based on the invasion ratio into the personal space described earlier. Furthermore, this weighting factor is assumed to be updated over time. Based on the above discussions, the characteristics of passenger's comfort recognition are summarized in Figure 16. Figure 16 is a model of comfort recognition based on situation awareness, which represents the effect of the Current Situation and the Future Status in situation awareness on passenger's comfort recognition.

This study has the following limitations. Since the experiment in this study was conducted in a VR environment using a head-mounted display, the difference in the perceived distance from the surrounding pedestrians and the narrow field of view may have affected the comfort recognition. Moreover, the biased participants, limited number of participants, and limited scenes are other limitations of this study. Further studies on the participants with a balance of gender and age including the older people, expanded samples and scenes, and real vehicles should be conducted as future works to overcome these limitations.

7 CONCLUSIONS

The purpose of this study is to clarify the characteristics of passenger's comfort recognition, that is, how the passenger feels comfortable depending on the behavior of the surrounding pedestrians and the vehicle when the personal mobility vehicle moves autonomously in a crowded environment. An experiment was conducted to obtain subjective assessment of passenger comfort using a VR simulator. By focusing on situation awareness as a process affecting passenger's comfort recognition, the influence of situation awareness on passenger's comfort recognition was analyzed and the characteristics of passenger's comfort recognition were discussed. The followings are the findings obtained in this study:

- The invasion ratio of pedestrians into the personal space has a significant impact on the passenger's discomfort.

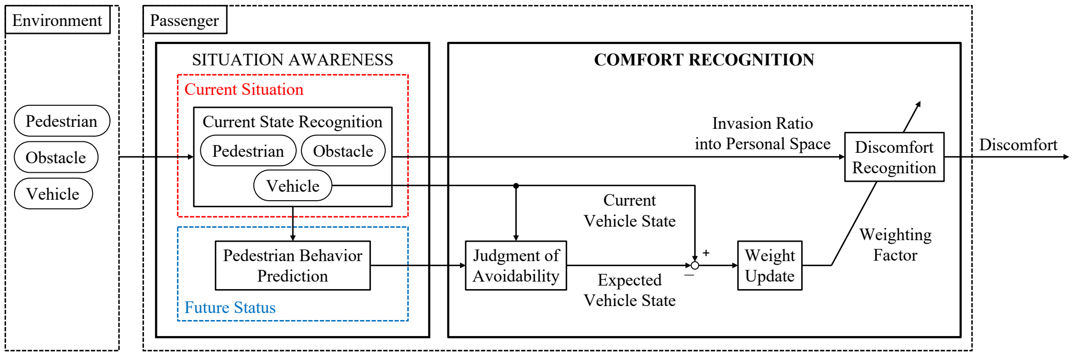


Figure 16: Characteristics of passenger's comfort recognition.

- Discomfort becomes stronger when a PMV does not take any actions to avoid approaching pedestrians, which will invade the personal space in the near future, even though it can, and when this status continues for a certain time period.
- Passenger's comfort recognition can be expressed using the Current Situation and the Future Status of the situation awareness as inputs.

The experiment conditions and the number of participants were limited in this study. Thus, examining the characteristics of comfort recognition in experiments with more diverse environmental conditions and larger sample size is our future work. Furthermore, we will propose and develop a comfortable autonomous navigation method based on the characteristics of passenger's comfort recognition.

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