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Paper:

Autonomous Motion Planning in Pedestrian Space Considering Passenger Comfort

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In this study, we proposed an autonomous motion planning method for improving passenger comfort while ensuring safety, particularly with respect to mobility scooters used by elderly people. We proposed a trajectory planner for restricting vehicle behaviors with large accelerations and jerks by selecting a safe trajectory from a set of preset trajectories. Then, based on this trajectory planner, we developed an autonomous motion planning method with four different driving modes, and evaluated the effectiveness of the method through a numerical simulation. The simulation results demonstrated that the proposed method increased comfort without compromising on safety.

Keywords: motion planning, autonomous locomotion, pedestrian space, passenger comfort, mobility scooter

1. Introduction

In recent years, the number of elderly people in Japan has been increasing with the aging of the population, along with the number of people with physical disabilities and dementia among the elderly. It is considered difficult for elderly people to live independently, owing to deteriorations in their physical and cognitive functions. Nevertheless, maintaining an independent lifestyle is a prominent issue. Maintaining the frequency of going out has been considered important for maintaining an independent lifestyle [1, 2]. As such, it is becoming more important to compensate for deteriorations in physical functions, and support traveling outdoors. There are great expectations for mobility scooters as devices for assisting such short-distance travel for elderly people, and the number of mobility scooters in use is increasing. However, approximately 150 traffic accidents occur per year involving electric wheelchairs, including mobility scooters [a]. In addition, because accidents involving electric wheelchairs and pedestrians (including those with injuries) are not treated as traffic accidents, these accidents do not appear in the traffic accident statistics. Furthermore, 12% of users with mobility scooters are suspected of having cognitive impairments, and fatal accidents involving them have occurred at railroad crossings, paved roads, and concave steps [b]. Based on the above background, we aim to construct a slow-speed mobility system for a mobility scooter, for securing the safe locomotion of the elderly by an autonomous driving function.

A mobility scooter is categorized as a walking assistance device according to the Japanese Road Traffic Law, and is regarded as a pedestrian. Thus, it can run in a pedestrian space, such as a sidewalk or a shopping street. There are other pedestrians in the pedestrian space where the scooter passes, i.e., the space is not limited to mobility scooters. Therefore, as a requirement for autonomous locomotion in a pedestrian space, the primary safety concern is avoiding collisions with pedestrians existing in the vicinity. As a motion planning method for avoiding collisions with dynamic obstacles such as pedestrians, dynamic window approach (DWA) [3], used for avoiding static obstacles, has been extended to avoiding dynamic obstacles [4–6], and a method for avoiding dynamic obstacles [7] has been proposed based on the concept of velocity obstacle [8]. In addition, a method [9] considering a pedestrian model and a method [10] considering human behavior by inverse reinforcement learning have been proposed for autonomous locomotion in an environment with dynamic obstacles. However, when safety is emphasized as a vehicle autonomously moves through a pedestrian space, it can be assumed that sudden braking or turning will occur to avoid collisions with pedestrians, resulting in poor riding comfort. Therefore, it is necessary to consider not only safety, but also passenger comfort, when planning motion in a pedestrian space.

There are existing studies considering passenger comfort when generating travel paths. Gulati et al. [11] proposed a method for expressing discomfort as a weighted sum of the total travel time and the time integrals of various momentums (acceleration and jerk), satisfying boundary conditions such as the position and speed at the endpoints of the path, and generating a path to minimize discomfort. Bevilacqua et al. [12] proposed a method for deriving a clothoid curve that minimized jerk from the waypoints of a standard path, and used it as a traveling path. Morales et al. focused on the distance to an obstacle and the translational and rotational velocities and accelerations as the factors related to comfort, and calculated human-comfort map (HCoM) composed of these factors, based on subject experiments [13]. They generated paths using the HCoM that allowed for comfortable indoor movement [13, 14]. In addition, Morales et al. studied a comfortable path even when passing by a single pedestrian in a corridor in an indoor environment [15]. However, these existing methods assume, e.g., no obstacles, or only static obstacles, and limited dynamic obstacles (such as pedestrians). Thus, the environment in which there are more than a few pedestrians is not assumed.

Based on the above, this research aims to construct an autonomous motion planning method for improving passenger comfort while ensuring movement safety in a pedestrian space where there are multiple dynamic obstacles (such as pedestrians). In this study, our target is a mobility scooter as a vehicle, and an elderly person as a passenger.

Section 2 describes the method for improving comfort while ensuring safety. Section 3 describes the autonomous motion planning method, including the method devised in Section 2. Then, Section 4 describes a numerical simulation for evaluating the effectiveness of the proposed method, along with its evaluation results and discussions. Finally, Section 5 summarizes the findings obtained in this study.

2. Examination of Methods to Improve Passenger Comfort

2.1. Target Comfort

In existing motion planning methods, the velocity and angular velocity of a vehicle are determined in consideration of potential collisions with static objects and other traffic participants. However, if the occupant of a vehicle with autonomous locomotion is an elderly person, he/she may have a deteriorating ability to maintain their current posture, owing to the effects of muscle weakness under aging. Therefore, owing to the inertial force generated as the vehicle runs, the posture may not be maintained, or the riding comfort may be deteriorated. Accordingly, in this study, we examine comfort from the perspective of posture retention and riding comfort of passengers, and examine a method for improving comfort. The parameters that affect posture retention and riding comfort are acceleration and jerk, which occur when the vehicle is running. In this study, the lateral acceleration and lateral jerk generated by the steering of a mobility scooter are investigated.

One method of improving comfort is to limit the acceleration and jerk generated during running. Therefore, limit criteria of acceleration and jerk are set, from the perspective of posture retention and riding comfort in elderly people. In a study by Ohno [c], the relationship between the acceleration in a standing position on a train and the proportion of elderly people who cannot hold their postures was investigated. It was found that 60% of elderly people can hold their posture at an acceleration of approximately 0.5 m/s^2 in a case of slow-speed motion vibration, e.g., passing through a curve. The study was an evaluation of the standing state, and although the standing state is different from the sitting state (i.e., how elderly people use a mobility scooter), it is also more unstable than the sitting state; thus, in a standing state, it is also difficult to maintain a posture. Based on the results for the standing state, it is thought that a sufficient limiting criterion can also be set for the sitting state. Thus, the limiting criterion for acceleration is set to 0.5 m/s^2. Regarding jerk, we set the limiting criterion considering a vibration evaluation index [16] for comfort as specified in ISO 2631, from the perspective of the relationship between the amplitude and frequency of acceleration within a range that is comfortable (less than 0.315 m/s^2). The solid line in **Fig. 1** shows the relationship between the allowable acceleration a and the frequency f; within which the vibration evaluation index falls within the comfortable range. This relationship between a and f is obtained by dividing 0.315 m/s^2 with the correction coefficient at each frequency, based on the horizontal whole-body vibration frequency characteristics in sitting, standing, and supine positions specified in JIS B7760 [17]. Here, assuming that the acceleration has an amplitude of a and a vibration of frequency f, the jerk j can be expressed with the acceleration a and frequency f, as shown in Eq. (1). The relationship between jerk and frequency within which the vibration evaluation index falls within the comfortable range is calculated, and the relationship indicated by the broken line shown in **Fig. 1** is obtained. As shown, if the jerk is 0.7 m/s^3 or less, the vibration evaluation index falls within the comfortable range. Based on these results, the jerk limitation criterion is set to 0.7 m/s^3.

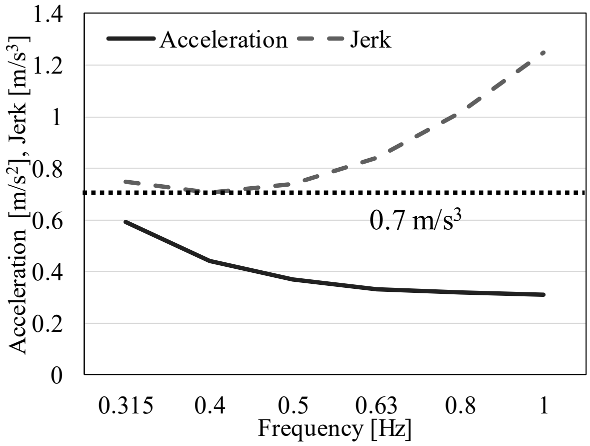


Fig. 1. Relation between acceleration/jerk and frequency, which stays in comfortable range.

$$j = 4af \quad (1)$$

2.2. Path Selection from Path Candidates with Restricted Vehicle Behavior

One method of limiting the acceleration and jerk generated during traveling is to limit the controllable range of the vehicle speed and steering angle, and to limit the vehicle behavior so that large accelerations and jerks are not generated. However, if the controllable range of vehicle behavior is limited in this way, even if it is determined that the vehicle may collide with pedestrians in the pedestrian space, it may be difficult to avoid such collisions, owing to the limited vehicle behavior. Thus, there is a possibility that safety cannot be secured. After considering the safety in this way, i.e., when trying to select a vehicle behavior that satisfies safety constraints from restricted vehicle behaviors, the traveling safety can interfere with the passenger comfort. Suzuki et al. [18] devised a method for generating a path by combining preset short paths, for the purpose of generating a smooth path for a mobile robot to avoid pedestrians. In the method of Suzuki et al., a candidate path satisfying a vehicle behavior constraint is held in advance, and a path that does not collide with a pedestrian, that is, a path that satisfies the safety constraint, is selected for locomotion. Thus, it is possible to prevent interference between the safety and comfort of passengers.

Therefore, in this study, we devise a method for holding path candidates that a vehicle can travel in advance, and for selecting a path from the stored candidates that is safe and does not collide with surrounding traffic participants (and which can approach a goal). To generate a path that satisfies the acceleration and jerk limits in advance, we use the path generation method proposed in Howard et al. [19]. Steps 1 to 3 for selecting a path in the method are shown below. The "process before running" is a process that is performed before the vehicle starts running, and the "process during running" is a process that is repeatedly performed while the vehicle is running.

1. Process before running: a set of possible target states is generated for the vehicle mechanism, along with path candidates.

2. Process during running: the pre-generated path candidates are ranked according to their ability to reach the goal.

3. Process during running: the possibility of collision with surrounding pedestrians is evaluated from the path candidates with the highest rank, and the path that satisfies the threshold is selected.

The "ability to reach the goal" in the above procedure is evaluated based on the distance from a point where the vehicle can reach along the path candidate to the goal, and the attitude angle of the vehicle with respect to the goal. In addition, the "possibility of collision with surrounding pedestrians" is predicted based on the premise that the position and speed information of pedestrians can be acquired during locomotion by using a sensor mounted on the vehicle. The probability of a pedestrian existing at a point where the vehicle can reach along the path candidates is evaluated. We consider that comfort can be improved while securing safety in locomotion, by limiting the acceleration and jerk values set in the previous section when generating the path candidates.

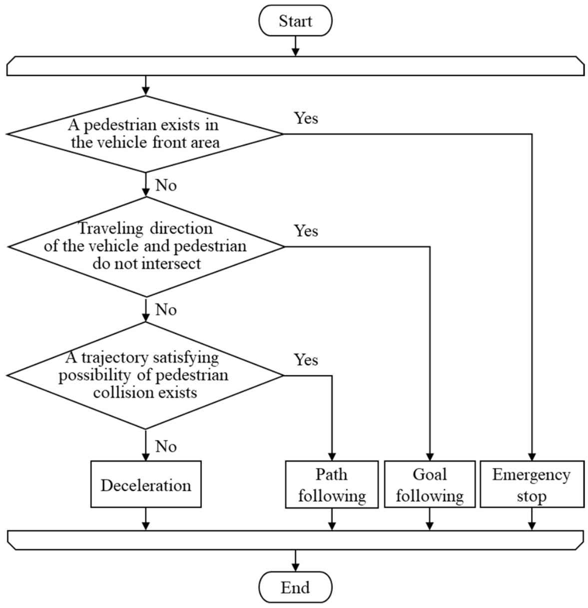


Fig. 2. Flowchart of the proposed autonomous motion planning method with four different driving modes.

3. Construction of Autonomous Motion Planning Method

To improve passenger comfort, we construct an autonomous motion planning method comprising path selection from path candidates with restricted vehicle behaviors, as described in the previous section. This method is composed of four driving modes for the vehicle: "path following," "goal following," "deceleration," and "emergency stop." The driving mode is selected according to the flow shown in **Fig. 2**. Definitions of the driving modes and their selected conditions are shown below.

1. Path following

   In this mode, the vehicle travels along a path selected by the path selection method described in Section 2.2. It is selected when there is a path that meets the threshold for the possibility of collision with a pedestrian among the path candidates generated in advance.

2. Goal following

   This is a mode for driving to a goal without setting a complicated path. It is selected when the possibility of collision with pedestrians in the pedestrian space is low, and specifically, when the vehicle's traveling direction vector and pedestrian's traveling direction vector do not intersect.

3. Deceleration

   In this mode, the vehicle decelerates when it cannot ensure safety while running. It is selected when there are no paths meeting the threshold regarding the possibility of collision with pedestrians.

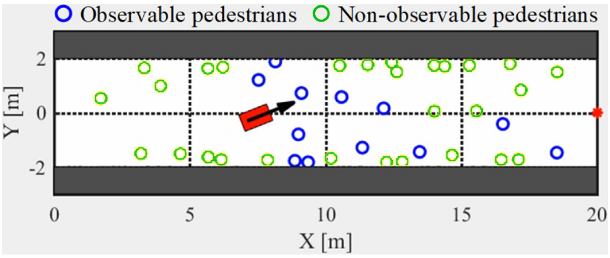


Fig. 3. Overview of the simulation scene.

4. Emergency stop

   This is an emergency stop mode for avoiding collisions with pedestrians. It is selected when a pedestrian enters the area in front of the vehicle.

In the constructed autonomous motion planning method, the path candidates used in the path selection for "path following" are generated by limiting the acceleration and jerk. Therefore, it is considered that the comfort of passengers can be improved without reducing the safety in locomotion.

4. Evaluation of Autonomous Motion Planning Method

The purpose of the evaluation is to determine whether the autonomous motion planned by the proposed method can improve passenger comfort without impairing safety. Assuming an environment with a crowded pedestrian space, numerical simulations are performed for a mobility scooter running based on the autonomous motion planning method described in the previous section, and the proposed method is evaluated from the viewpoints of comfort and safety.

4.1. Simulation Conditions

The numerical simulations are conducted for a mobility scooter and pedestrian on a road with a width of 4 m, extending in the positive direction of the X-axis. **Fig. 3** depicts the evaluation environment for the numerical simulation. The shape of the vehicle is a rectangle with a length of 1.1 m and width of 0.65 m. The initial position of the vehicle is $(X,Y) = (0,0)$, the goal is $(20,0)$, and the vehicle is moved according to the preset motion planning method. Each pedestrian is assumed as a circle with a diameter of 0.4 m, and each pedestrian is moved according to the "social force model" used in the study by Johansson et al. [20]. For half of the pedestrians, their initial X coordinates are set randomly in the range of 0–10 m and are given a destination in the positive direction of the X-axis. For the other half, their initial X coordinates are set randomly in the range of 10–20 m and are given a destination in the negative direction of the X-axis. The initial pedestrian velocity is set randomly in the range of 1.1–1.3 m/s. We consider that the effectiveness of the motion planning method is affected by the degree of congestion in the pedestrian space, and thus, set the conditions for the number of pedestrians as 10, 20, and 40. The duration of the simulation cycle is 0.1 s.

It is assumed that the scooter is equipped with a sensor that can detect pedestrians in front of the vehicle. We assume that pedestrians within 30 m can be observed. However, we assumed that observation is not possible if more than 75% of the pedestrian is visible from the vehicle. Based on the observed pedestrian position and velocity, we generate and update the pedestrian existence probability distribution after a certain period of time (1.5 s), and use it to evaluate the possibility of collision with surrounding pedestrians during path selection.

4.2. Evaluation Methods

To evaluate whether the autonomous motion planning method can improve the comfort of passengers while ensuring safety in locomotion, the motion planning method constructed in this research and the DWA with collision suppression cone (DWA-CSC) of Guan et al. [6] are compared and evaluated. As a comparison target of the proposed method, it is appropriate to select a method that is generally used for autonomous motion planning. DWA [2] is a method that is generally used in mobile robots, but it is a method that avoids static obstacles. Therefore, DWA-CSC, which is a method that adds an evaluation term to avoid dynamic obstacles such as pedestrians, is selected as an existing method for comparison.

To evaluate passenger comfort, the maximum lateral acceleration [m/s^2] and maximum lateral jerk [m/s^3] are used as evaluation indices. The lateral vehicle acceleration a is calculated as shown in Eq. (2) using the vehicle speed V, steering angle θ, and vehicle wheelbase L, and the lateral jerk is the differential value of the acceleration. To evaluate the safety, we consider that it is safer for vehicles and pedestrians to avoid collisions; thus, the number of collisions between the vehicle and pedestrians is used as the safety evaluation index. A collision is determined when the vehicle region and pedestrian region overlap. Numerical simulations for 100 scenes with different pedestrian initial conditions are conducted for the proposed method and existing method [6], and the average values of the evaluation indices are compared and evaluated.

$$a = \frac{V^2 \tan\theta}{L} \quad \quad (2)$$

4.3. Evaluation Results

Figure 4 depicts the time ratios of the driving modes selected by the proposed autonomous motion planning method under conditions of different number of pedestrians. As the number of pedestrians increases, i.e., the density of pedestrians in the pedestrian space increases, the proportion of time for which path following mode is selected increases. This can be attributed to the increase in the degree of congestion in the pedestrian space, resulting in an increased frequency of intersections between the

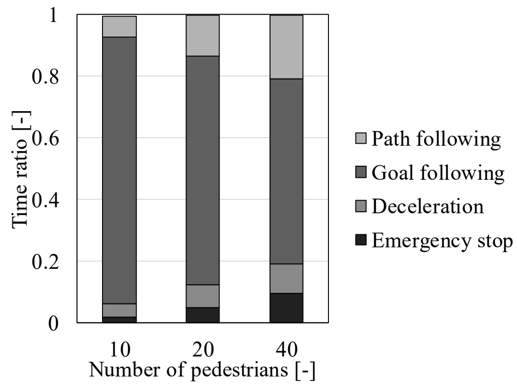


Fig. 4. Time ratio for each driving mode during autonomous locomotion using the proposed method.

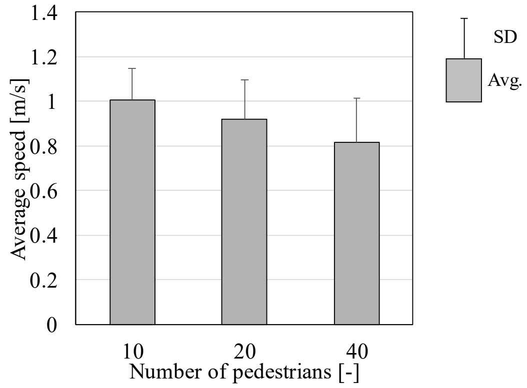
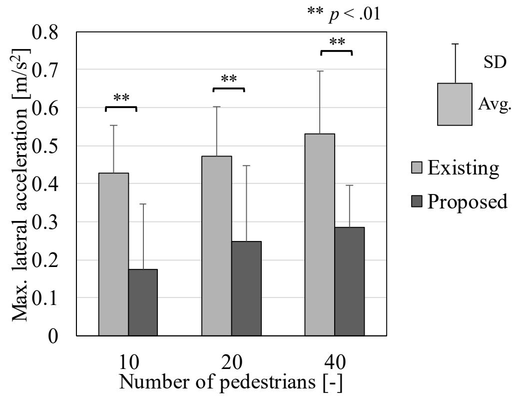
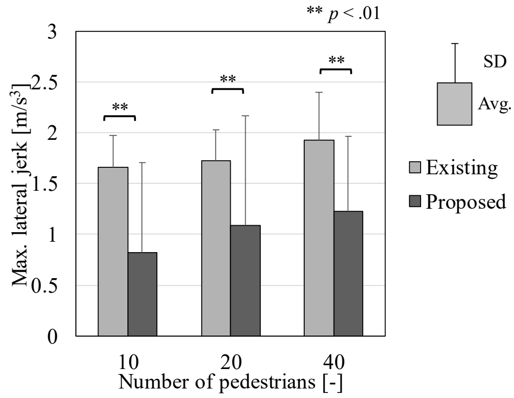


Fig. 5. Average speed during autonomous locomotion using the proposed method.



(a) Maximum lateral acceleration



(b) Maximum lateral jerk

Fig. 6. Comparison of passenger's comfort-related indices between existing and proposed method.

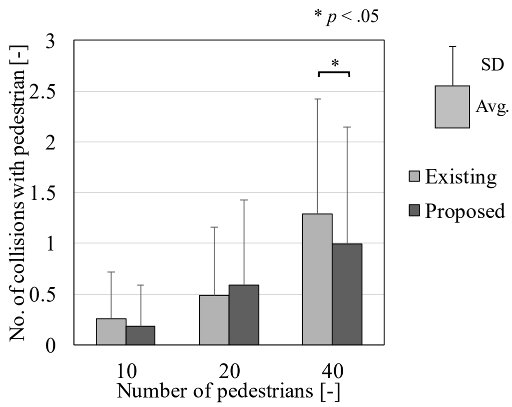


Fig. 7. Comparison of safety-related index (number of collisions with pedestrians) between existing and proposed method.

vehicle's traveling direction and pedestrians' traveling directions, making it impossible to select the goal following mode. In addition, when the number of pedestrians is large, the proportions of time spent in the driving modes of deceleration and emergency stop are large. As a result, the average speed during running tends to be low (**Fig. 5**).

Figure 6 depicts the comparison results of evaluation indices for comfort when the vehicle is driven based on the existing and proposed methods. The evaluation index of each method tends to increase when the number of pedestrians is large. Nevertheless, the evaluation index of the proposed method is compared with that of the existing method by using the Mann-Whitney U test for each pedestrian number condition, and the results are found to be significantly lower ($p < 0.01$). From these results, it can be seen that by selecting a path from the path candidates with restricted vehicle behaviors, such that the acceleration and jerk do not exceed certain limits, the comfort of passengers is improved in comparison with the existing method, regardless of the density of the pedestrian space. In addition, as a result of comparing the average values of the number of collisions between the vehicle and pedestrians (a safety evaluation index) between the existing method and proposed method (**Fig. 7**), it is found that the number of collisions increases in both methods as the number of pedestrians increases. Although the number of collisions increase according to the number of pedestrians, there is no significant difference between the methods as a result of comparing the number of collisions under the condition of 10 and 20 pedestrians. However, there is a significant difference in the Mann-Whitney U test under the condition of 40 pedestrians ($p < 0.05$). In addition, the relative speeds of the vehicle and pedestrian at the time

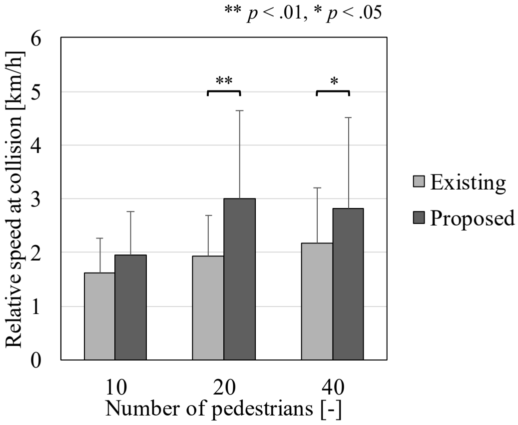


Fig. 8. Comparison of relative speed at collision between existing and proposed method.

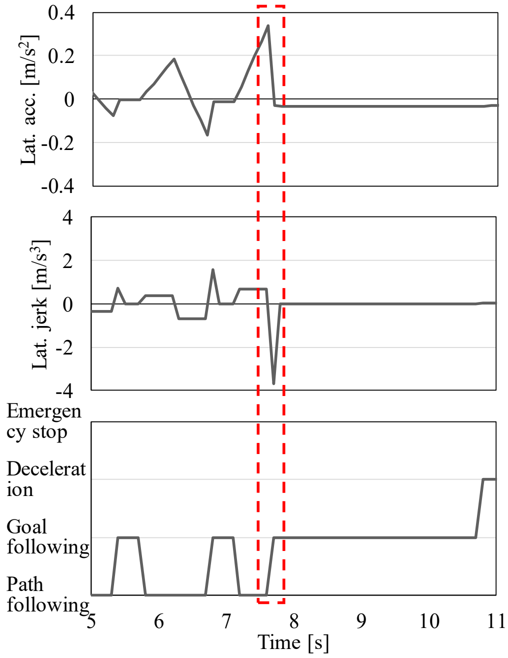


Fig. 9. Transition of lateral acceleration, lateral jerk, and driving mode during autonomous locomotion using the proposed method.

of collision are compared and evaluated using the existing and proposed methods, based on the Mann-Whitney U test. Although there is a significant difference between existing and proposed methods, the average value of the relative speed is low (approximately 2–3 km/h) for both methods (**Fig. 8**). From the above, it is found that the proposed motion planning method can improve passenger comfort while ensuring the same level of safety as existing methods, regardless of the density of the pedestrian space.

4.4. Discussion

As shown above, passenger comfort can be improved by selecting a safe path from the path candidates satisfying certain criteria regarding acceleration and jerk. However, behavior exceeding the jerk criterion was observed. **Fig. 9** depicts the lateral acceleration, lateral jerk, and the driving mode selected in the proposed method along the time axis. As shown in the figure, the jerk exceeds the set criterion (0.7 m/s^3). Notably, when the jerk exceeds the limit, it corresponds to the time at which the mode changes from path following to goal following. It is considered that the speed and steer angle change discontinuously at the time of this mode change, resulting in a significant change in the acceleration and jerk. Therefore, to prevent the generation of large accelerations and jerks, it is necessary to properly design a method for switching the driving mode.

To secure the safety of locomotion, the proposed method holds path candidates that a vehicle can travel in, in advance, and selects a safe path from the held candidates that does not collide with the surrounding traffic participants. However, as depicted in **Fig. 7**, a collision between a vehicle and pedestrian occurs in some scenes of the simulation. As described in Section 2.2, the possibility of collision on each path is predicted and evaluated, based on the probability of the pedestrian's presence at the point which the vehicle can reach along the path. However, if the predicted existence probability and the actual existence probability differ owing to the influence of pedestrians that cannot be observed, or if the movement of pedestrians is different from the prediction, when the vehicle approaches the pedestrian and its sudden deceleration is delayed, a collision may occur. Moreover, as a characteristic of the pedestrian model used in this study, a certain pedestrian can move based on the action of a vehicle, another pedestrian, or a wall. Therefore, there is a possibility of a pedestrian moving in the direction in which the vehicle exists, and as a result, there may be cases where the vehicle collides with a pedestrian. A collision with a pedestrian can occur even when the vehicle is stopped at zero speed, and it is presumed that the cause of the collision is as described above.

It is suggested that the proposed method does not show any decrease in safety, and can improve safety in a crowded pedestrian space. To consider the factors that improve safety in a congested environment, the numbers of collisions when autonomously moving are compared between three methods (the existing method, the proposed method, and the proposed method with path candidates without restriction of vehicle behavior) under the most crowded pedestrian condition (40 pedestrians) (**Fig. 10**). The Mann-Whitney U test is used to compare the existing method with the proposed method that does not limit vehicle behavior. There is no significant difference, but when compared with the proposed method that limits vehicle behaviors, there is a significant difference ($p < 0.05$). Therefore, it can be inferred that limiting the vehicle behavior to the path candidates led to the improvement in safety. By limiting vehicle behaviors, sudden changes in vehicle position and orientation are suppressed, and sudden changes in the positional relationships between the

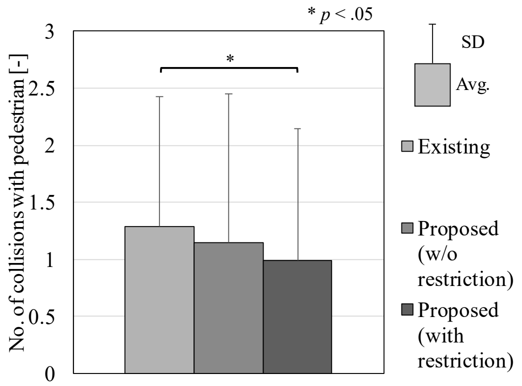


Fig. 10. Comparison of safety-related index between existing and proposed method with/without kinematic restriction (number of pedestrians: 40).

vehicle and pedestrians are suppressed. It is thought that the number of collisions with pedestrians is decreased because it becomes possible to select a proper path, and decelerations and emergency stops can be performed with sufficient margins for the pedestrians.

5. Conclusions

Aiming to construct an autonomous motion planning method that improves the comfort of passengers while ensuring safety in locomotion in a pedestrian space, we first devised a method for improving comfort. Then, we constructed an autonomous motion planning method in a pedestrian space based on the devised method. Finally, the effectiveness of the proposed method was evaluated by performing a numerical simulation using the constructed motion planning method, and comparing it with an existing method. As a result of performing the above, the following results were obtained.

- As a method of improving passenger comfort without deteriorating safety, we devise a method to select paths with low possibility of collision with surrounding pedestrians among the path candidates that limit vehicle behaviors with large acceleration and jerk.
- As a result of evaluating the effectiveness of the proposed autonomous motion planning method using a numerical simulation, it is found that the proposed method can improve comfort while ensuring the safety in locomotion.
- It is suggested that when the proposed method is used in a crowded pedestrian space, both comfort and safety can be improved by limiting vehicle behaviors.

Directions for future research include improving the method of switching the driving mode to prevent the generation of acceleration and jerk from exceeding the limits. In addition, we intend to implement the proposed method on a mobility scooter, and study the improvement in passenger comfort in a real environment. Furthermore, when traveling in a real environment (including outdoors), road surface conditions may also affect the comfort of passengers. Thus, we plan on investigating an autonomous motion planning method that can realize comfortable movement for passengers while considering these factors.

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