Behavior Analysis of Passengers on Bench Seats in a Train Collision

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Research on a previous train collision clarified the occurrence of a pattern whereby passengers sitting on a bench seat sustained chest injuries caused by the dividers installed to the side of the seat. Numerical simulations were performed under several conditions to estimate the likelihood of thoracic injuries fitting this pattern. According to the results, rib deformation caused to passengers by panel-type side dividers is less than that caused by the tubular type, meaning that fewer thoracic injuries occur with the panel-type divider. An impact test was also performed to verify the results of these numerical simulations.

Keywords: safety, ergonomics, train collision, minimization of injuries, divider, bench seat, occupant behavior analysis

1. Introduction

A number of approaches are taken in rail transportation safety, but the focus is always on the two aspects of either preventing accidents or reducing injuries and avoiding a domino effect of injuries if an accident does occur. The Railway Technical Research Institute conducts safety studies in both these areas [1]. Research into injury reduction in the event of a train collision focuses on examining not only the primary impact of the vehicle collision but also the secondary impact caused by the force of the collision hurling passengers against interior parts of the compartment or against other passengers. In primary collision studies, the car body structure is examined, while secondary collision studies focus on examining occupant-related kinematic factors. This paper reports on the results of secondary collision studies for passengers sitting on a bench seat.

It is necessary to clarify the individual situations of passengers during secondary collisions in order to propose measures against injuries caused by such accidents. Estimate analysis of passenger situations as well as research into accidents themselves is essential for this purpose. Analysis for estimating information on passenger movement and the contact forces to which passengers are subjected is called Occupant Behavior Analysis. We conducted numerical simulations of secondary collisions indicating a pattern in which passengers on bench seats may sustain chest injuries after striking a divider, and analysis using an impact test dummy was conducted in order to confirm these results.

2. Characteristics of injuries sustained by passengers sitting on bench seats

Previous research into train collisions clarified that injury patterns depend on the car interior, and in particular on the seats [2,3]. In this research, accident data were reclassified by the passenger positions (i.e. standing or sitting) found in commuter trains equipped with bench seats. The accident in question occurred when a following train crashed into a preceding train at a speed of 30 km/h. Figure 1 shows the distribution of body areas where passengers were injured (Injured areas) and Figure 2 shows the distribution of the objects that caused injury (Injuring objects). In terms of injured body areas classified by a standing or sitting position, the head was the most commonly injured for standing passengers, accounting for 13 people (20%), while the chest was the most common for sitting passengers with 14 people injured (48%). In terms of the objects that caused injury, 45 people (80%) standing were injured by the floor, handrails or other passengers. The injuring objects for those in a sitting position were mainly handrails, accounting for 16 people (64%). The handrails adjacent to passengers seated on benches also act as a barrier between them and standing passengers, and are referred to as dividers. 15 of the

![Fig. 1 Distribution of injured body areas](image-url)
24 people injured while sitting on benches were positioned just adjacent to a divider or next to a vacant seat adjacent to a divider. Some of them were severely injured with broken ribs, and needed a month or more to recover. These figures suggest an injury pattern whereby dividers cause chest injuries to passengers sitting adjacent to them.

3. Numerical simulation of passenger movement

Numerical simulation was conducted to analyze passenger movement in the injury pattern outlined above, in which travelers are assumed to be sitting on a bench seat adjacent to a divider. The parameters of this analysis were selected with due consideration for further study on measures against injury. There were two steps in the analysis; in the first, the conditions of the divider types, the acceleration waves and the number of passengers were set with two levels each. In the second step, five divider models were installed, including the panel-type model used in the first step (the normal model) and four other models devised to counteract the injury pattern based on the results of the first step. The effects of these models on the occurrence of injury were compared.

3.1 Models of bench seat and divider

The bench seats had tubular dividers at each side in the case of the injury pattern outlined above in which passengers hit the dividers. A divider model of this type was therefore set at the side of a bench seat model (Fig. 3(a)), and a panel-shape divider of the type (Fig. 3(b)) seen more and more recently was also set. Both dividers were modeled using finite elements because the deformation of contact areas between human models and dividers was assumed to have an effect on human injury. Seats and seat backs were modeled approximately using rigid bodies because their deformation was assumed to have little influence on human injury. Table 1 shows the characteristics of the materials used for the models.

In the second step, a setup with panel dividers, impact acceleration A (see the following paragraph) and one seated passenger was defined as the normal condition. Five cases were analyzed, including the normal condition, a setup featuring a divider with a 50% reduction in frame endurance compared to the normal condition, one with a 50% reduction in elastic modulus compared to the normal condition, one with a 0.1-m urethane foam covering, and one filled with Theta Gel (GELTEC Co., Ltd), a shock-absorbing material. The cases with 50% reductions in endurance and elastic modulus were not assumed as realistic; rather, they were adopted to enable comprehensive examination of measures against injuries caused by train collisions.

![Fig. 3 Lateral views of bench seat models](Unit: mm)

<table>
<thead>
<tr>
<th>Table 1 Characteristics of seat and divider materials</th>
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<tr>
<td>Parts</td>
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</tr>
<tr>
<td>Pipe</td>
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<tr>
<td>Panel</td>
</tr>
<tr>
<td>Frame</td>
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<tr>
<td>0.2%</td>
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* The condition of panel divider frames in the first step was changed to another condition in the second step
3.2 Acceleration

Relative acceleration occurs between a car and its passengers when a train is involved in a collision. Two kinds of acceleration (Fig. 4) were set up with the same rate of change in momentum. These accelerations were assumed to differ in waveform as a result of differences in car construction. The acceleration values were set to satisfy conditions whereby the rates of change in velocity of the car floors were identical at $\Delta V=5 \text{ m/s}$ and the maximum value in the second acceleration was half that of the first acceleration. We called the first acceleration acceleration $A$ and the second one acceleration $B$.

![Fig. 4 Acceleration conditions](image)

3.3 Human model and the number of seated passengers

A human model with finite elements (the THUMS-AM50 Occupant model for PAM-CRASH, developed by the Toyota Motor Corporation) was used in this analysis, since it offers the most realistic human body simulation of all numerical human models today. The THUMS-AM50 is mainly used in numerical simulation analysis of automobile crash tests, and represents the average body of American male adults aged 30 to 40 (at 175 cm in height and weighing 77 kg).

In the first step, the effect of the number of seated passengers on injuries was studied using the two setting levels of one person and two people. In the second step, the effect of the dividers on injuries was studied with the condition of only one seated passenger.

3.4 Constraint conditions and friction conditions

The degrees of freedom of motion for the parts of models comprising rigid bodies were all constrained except in the running direction of the car. In the first step, a friction coefficient of 0.3 was assumed for every part with which passengers came into contact. In the second step, the friction coefficient between passengers and seats or seat backs was assumed as 0.4, and the value between passengers and other parts was assumed as 0.1. These dynamic friction forces were considered to have little effect on passenger movement, but were assumed to give a more realistic scenario than those used in the first step.

3.5 Results in the first step

In the first step, analyses were conducted under the conditions of two divider types, two acceleration waveforms and two values for the number of seated passengers. Figure 5 shows an example of the analysis for the case with a panel divider, acceleration $A$ and one person. The maximum chest deformation was adopted as an index of the likelihood of injury, because broken ribs were mainly expected in the case of chest injuries discussed here. Chest deformation was generally defined as the relative deformation between the spinal column and the breastbone[4]. In particular, the relative deformation between the spinal column and the ribs was used in the case of impact to the side of the body. The ten maximum deformations of the second rib to the eleventh rib were calculated, and the maximum value among them was defined as the maximum chest deformation (Fig. 6). Figure 7 shows the maximum deformations for passengers sitting by dividers for every condition. The maximum val-

![Fig. 5 Example of simulation with a passenger on a bench seat](image)

![Fig. 6 Time series of chest deformation data](image)
ues with panel dividers were less than those with tubular dividers for all combined conditions of acceleration waveform and the number of seated passengers. The maximum chest deformation against the panel type was \(-0.028 \text{ m}\) to \(-0.039 \text{ m}\), while the values for the tubular type were \(-0.096 \text{ m}\) to \(-0.126 \text{ m}\). This suggests that panel dividers reduce the likelihood of chest injury as compared to the tubular type.

The maximum chest deformation under the condition of two passengers was larger than that for one person. The degree of increase between one and two people is about 30%, or about \(-0.030 \text{ m}\) for the tubular type and about \(-0.010 \text{ m}\) for the panel type. This suggests that a case with two people has a higher likelihood of chest injury than with one person.

On the other hand, no difference between the results under accelerations A and B was seen.

Based on these results, the difference in the divider type was evaluated as the most influential factor in chest injuries among the condition variables.

### 3.6 Results in the second step

The results in the first step suggested that panel dividers offer a potential reduction in the occurrence of injuries. In the second step, a condition with a combination of panel dividers, impact acceleration A and one passenger was defined as the normal condition. Five cases were analyzed in which the divider had five different conditions, including the normal condition, one with a 50% endurance reduction in the divider’s frames, one with a 50% reduction in elastic modulus, one with a 0.1-m covering of urethane foam, and one filled with Theta Gel shock-absorbing material. Figure 8 shows an example of the analysis with the case specific to a divider covered with urethane foam, while Fig. 9 shows the maximum chest deformations for each case. The values are \(-0.060 \text{ m}\) in the case of the normal condition, \(-0.058 \text{ m}\) for the case with a 50% reduction in the divider frame endurance, \(-0.060 \text{ m}\) for the 50%-reduced elastic modulus case, \(-0.057 \text{ m}\) for the urethane foam case and \(-0.061 \text{ m}\) for the shock-absorbing material.

### 4. Experimental verification

An experiment was conducted using an impact test dummy to verify the results of the numerical simulation outlined above.

#### 4.1 Method

Two cases under the conditions of a panel divider and a tubular divider were verified. The other conditions of one seated passenger and acceleration A used in the numerical simulations were added.

A side-impact experimental dummy (Euro Sid-1) was used as the passenger to allow measurement of lateral chest deformation. This dummy is the average size of an adult male, and has three steel ribs representing the upper, middle and lower ribs of the human chest. Instruments to
measure deformation were installed in these ribs, and the dummy was seated at a distance of 0.27 m from its center to the divider. The Japan Automobile Research Institute's sled impact test equipment (HYGE) was used in this experiment, and the sled was launched with rapid acceleration using high-pressure gas.

Figure 10 shows the devices used to fix the dividers firmly on the sled. The devices were made of steel (SS400), and were designed with sufficient strength to ensure that the fixed dividers did not slide against the sled from the impact.

### 4.2 Experimental results

Figure 11 shows the acceleration data measured on the sled against the targeted value of acceleration A.

Figure 12 shows an example of the experiment with a tubular-type divider, while Fig. 13 shows that of the panel type and Fig. 14 shows the chest deformation results. The maximum chest deformation for the tubular type was 0.053 m, and that for the panel type was 0.026 m. Both values are smaller than those in the numerical simulation, but show the same tendency whereby the maximum chest deformation for the panel type is less than that for the tubular type. Furthermore, the experiments showed the same results as the numerical simulation in that the

![Image of acceleration waveform](image1)

**Fig. 11** Acceleration waveform of impact on floor of sled

![Image of impact test examples](image2)

**Fig. 12** Example of impact test for tubular divider

![Image of chest deformation data](image3)

**Fig. 14** Chest deformation data
maximum chest deformation for the tubular type appeared at the lower rib. These results supported those of the numerical simulation that the likelihood of chest injuries with the panel type is lower than that with the tubular type.

5. Conclusions

Previous train collision research clarified that injury patterns depend on car interiors, and in particular on the type of seat. Accident data relating to bench seats were therefore reclassified, and confirmed the pattern whereby passengers sitting at the end of bench seats suffered chest injuries due to the adjacent dividers. Numerical simulations of this pattern were conducted using a FEM human model. In the first step, these simulations were conducted under the conditions of two divider types (tubular and panel), two acceleration waveforms (Fig. 1) and two values for the number of people (one and two). In the second step, other simulations were conducted for the four cases in which dividers had a 50% reduction in frame endurance, a 50% reduction in elastic modulus, a 0.1-m urethane foam covering, and a shock absorption material filling. An experiment was conducted using sled impact test equipment to verify the results of numerical simulation for the two types of divider. These results are concluded as follows:

(1) Chest deformation with panel dividers was less than that with tubular dividers. The likelihood of chest injury with panel dividers is therefore lower than that with tubular dividers.

(2) Chest deformation increased by about 30% as the number of seated passengers increased from one to two.

(3) Assuming two trapezoidal accelerations with a rate of velocity of \( \Delta V = 5 \text{m/s} \) on the floor of the car, comparison of chest deformation under the two acceleration conditions showed no difference between them.

(4) There was no difference in chest deformation among the cases in which dividers had a 50% reduction in frame endurance, a 50% reduction in elastic modulus, a urethane foam covering or a filling of shock absorption material.

(5) Impact testing confirmed that chest deformation for panel dividers was less than that for tubular dividers.

Acknowledgement

These analyses focus on the injury patterns of passengers sitting on bench seats. It is important for safety research to continue analyses such as those described above step by step. Previous research has shown that injury patterns depend on car interiors, and in particular on seat types. Future behavior analysis of passengers will be conducted under the conditions of other car interiors such as cross seats.

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References