An Estimation of the Severity of Passenger Injuries Seated on a Longitudinal Seat in a Train Accident and Measures to Mitigate Harm Using Numerical Simulation

Kazuma NAKAI
Ergonomics Laboratory, Human Science Division

Daisuke SUZUKI
Vehicle & Bogie Parts Strength Laboratory, Vehicle Structure Technology Division

Shota ENAMI

Tomohiro OKINO
Ergonomics Laboratory, Human Science Division

Junichi TAKANO
Vehicle & Bogie Parts Strength Laboratory, Vehicle Structure Technology Division

It is of vital importance to enhance on-board passenger safety in the event of a train collision. In order to design the interior fittings to reduce passenger injury levels, it is necessary to examine the probability of such injuries. The purpose of this study is to grasp the severity of injuries suffered by occupants of longitudinal seats and to consider mitigation measures using FEM simulation. For this simulation, bench-end partitions were modeled on the basis of an FEM model. It was found that passengers seated on a longitudinal seat with a high risk of injury were those seated second-furthest and third-furthest away from the bench-end partition and that the severity of head injury decreased significantly with the presence of handrails.

**Keywords:** passive safety, interior fitting, longitudinal seat, survival factor

1. Introduction

It is of vital importance to enhance on-board passenger safety in the event of a train accident. In order to reduce passenger injury levels, it is necessary to examine the probability of such injuries. The impact phase is divided into two parts. One part is the collision between the railway vehicle and external objects, which is called the “primary impact”. The other relates to collisions between passengers and interior fittings, called “secondary impact”. The study in this report focuses on secondary impacts.

In order to design safety measures for interior fittings to reduce passenger injury levels from secondary impact, it is important to accurately identify the risk to occupants in the event of a train collision. In previous research [1], data about passenger injuries were categorized by occupant posture (i.e. standing or sitting) in the event of a commuter train collision. One accident in Japan involved a following train colliding with a preceding train at approximately 30 km/h. The results of research into this collision indicated that the dividers, found at each end of longitudinal seats, caused chest injuries to passengers sitting adjacent to them. However, since then there has been little research on this area in Japan, it is difficult to determine the risk to occupants through statistical methods. Consequently, passenger behavior and severity of injury in the event of a train collision were examined through sled tests and numerical simulation to identify the risk to passengers.

The severity of injuries depends on the acceleration pulse caused by the primary impact and the characteristics of interior fittings. Sled tests were conducted to clarify the relationship between these factors and severity of injury [2]. Sled tests reproduce accident conditions by using an acceleration pulse with a sled, onto which the interior fittings and the crash test dummy, a full-scale anthropomorphic test device, are placed. The conditions of sled tests which can be carried out are restricted because of testing equipment specifications. Therefore, in order to overcome the constraints of physical tests, numerical collision simulations are used to perform parametric studies efficiently, overcoming the constraints of physical tests. The numerical simulations performed on computers replicated sled tests by using interior fitting models and dummy models [3].

The UK’s Railway Safety and Standards Board has established a Railway Group Standards GM/RT2100 (RGS) [4] to develop a crashworthy structural design, and this standard is considered to be one of the most advanced specifications of its type. This standard provides a sled test method to evaluate the injury that is caused to passengers who are seated in a transverse seating arrangement. However, there is no standard to evaluate the injury that is caused to passengers occupying longitudinal seating arrangements. In other words, it can be said that an evaluation method for the passengers occupying longitudinal seats is yet to be established. Commuter trains in a number of major cities in Japan have longitudinal seating arrangements, which is similar to that observed in some metro trains in European countries. Therefore, it is important to ensure the safety of the passengers seated on longitudinal seats.

Recently, research was conducted about such passengers [2, 3, 5]. One of these studies [5] observed that handrails exhibit an ability to reduce the severity of thorax injury among passengers and the velocity of head at secondary impact by using multibody simulation. This simulation however was conducted using the simple rigid model of interior fittings. Therefore, it was difficult to make use of the interior fitting design from the shape, material and structural points of view.

The purpose of this study is to estimate the severity of injuries suffered by occupants of longitudinal seating and to consider mitigation measures using finite element simulation.
2. Modelling of bench-end partitions

Collision with the bench-end partition at the ends of longitudinal seats end was studied. The bench-end partition was modelled with a finite element to consider possible mitigation measures to reduce injury from a shape, material and structural point of view. The precision of this model was verified by comparison with the impact test.

The numerical analysis software, MADYMO version 7.6, was used for finite element simulation. This software is widely used in the auto industry. The behavior and the severity of passenger injuries were evaluated with models of passengers, using this software.

2.1 Bench-end partition model

The outside of the bench-end partition is covered with resin materials. The inside is comprised of the steel frame and polyurethane filled in the frame. The bench-end partition is fitted in the train at a fixed position as shown in Fig. 1. This type of partition is very popular in Japan. The bench-end partition was modelled with the finite element based on the shape, material and structure of the bench-end partition. The number of nodes were approximately 18,000 and the number of elements were approximately 48,000 in the model shown in Fig. 2. The physical properties of material like Young’s modulus, yield stress, density, and so on, were defined based on the result of another test to obtain the physical properties.

![Fig. 1 Structure and material of bench-end partition](image)

![Fig. 2 Bench-end partition model](image)

2.2 Model verification

The precision of the bench-end partition model was verified by comparison with the impact test.

2.2.1 Method of impact test

Figure 3(a) and 3(b) show the appearance of the bench-end partition component experiment. The bench-end partition was struck by the impactor at positions A and B. The inside at position A is steel frame and the inside at position B is polyurethane. The impact velocity was approximately 16 km/h. The reaction force and deflection of the bench-end partition at the impact were measured. The force was calculated using acceleration measured by accelerometer in the impactor. The deflection was measured with displacement gauge using a magnescale.

![Fig. 3 Appearance of the bench-end partition component experiment and analysis](image)

2.2.2 Comparison with impact analysis

The impactor model was struck with the bench-end partition model under the same conditions as the impact tests shown in Fig. 3(c). Figure 4 shows the comparison between test and analysis. The horizontal axis represents the deflection and vertical axis represents the force. This figure shows that the analysis results, the maximum deflection values, force valued and process to their maximum values, almost corresponds with the test results.

3. Estimation of injuries and countermeasures

The severity of injuries of the occupants on the longitudinal seat was estimated and the counter measures to mitigate it were considered by using dummy models and bench-end partition models verified in the preceding chapter.

3.1 Estimation of the severity of injuries

3.1.1 Analysis conditions

As shown in Fig. 5, dummy models were seated on longitudinal seat model. This seat model was constructed by rigid model [6]. The bench-end partition model was arranged at the end of seat model under the same conditions as those found with an actual lay out of a train.

In the event of a collision, there is relative deceleration (acceleration) between the carbody and passengers on board.

Accelerations in the direction of the track were used as input. The accident scenario was a train colliding with a 40 t truck on a level crossing at 60 km/h.
Dummy models were seated on the longitudinal seats model. Four initial seating positions (Positions A, B, C and D) and four initial seating postures (Forward, Forward 10 mm, Right 10 degree and Left 10 degree) as shown in Fig. 6, were used, which comprised fifteen conditions.

The dummy behavior was evaluated using the collision position to bench-end partition of the dummy’s head from the floor, and the Secondary Impact Velocity to the bench-end partition of the dummy’s Head (SIVH).

### 3.1.2 Dummy behavior and injury criteria

The dummy injuries were evaluated using the HPC (Head Performance Criterion) and the RDC (Rib Deflection Criterion) that have been used extensively for assessing the safety of automotive occupants [7]. The HPC and RDC criteria are used to indicate the likelihood of head and thorax injuries arising from the lateral impact. Reference limit values for HPC and RDC are 1,000 and 42 mm respectively. In this paper, these values were used as a limit values. The HPC calculation method is the same as the HIC (Head Injury Criterion) calculation method as shown in (1), which is defined in the RGS [4]. The dummy’s thorax consists of three rib modules, i.e. the upper rib, the middle rib and the lower rib. The maximum values measured in the rib deflection in each of the rib modules were defined as the RDC.

\[
HPC = \left( \frac{\int_{t_1}^{t_2} a(t) \, dt}{(t_2 - t_1)} \right)^{2.5} \left( \frac{I_{25}}{I_{max}} \right) 
\]  

(1)

### 3.1.3 Results and discussions

Figure 7 shows HIC and RDC values. The HIC values varied according to the initial seating position and the figure shows that the severity of injury of the dummy in positions B and C was higher than in other seating positions. On the other hand, RDC values were below the limit value in all conditions. It was found that the risk to the head was higher than the risk to the thorax.
The above mentioned results demonstrate that the HIC for Positions B and C was progressively higher than in other positions. This paragraph discusses the reasons that caused this outcome. Figure 8 shows the comparison of SIVH. From Figure 8, it was found that the SIVH in positions B and C was higher than other positions. It is likely that the HIC for positions B and C was higher than other positions because of the difference in SIVH.

3.2 Consideration of countermeasures

In the preceding section, it was found that the risk to passengers’ heads in Positions B and C was high. Possible countermeasures were considered for these passengers in this section.

3.2.1 Countermeasures for passengers in positions B and C

Countermeasures were then considered for passengers in Positions B and C. The design of the steel frame in the bench-end partition was changed to reduce the strength of the partition. By using a steel frame model thinner by 30%, severity of injuries of passengers in Positions B and C was evaluated. The initial seating posture was Forward.

Figure 9 (a) shows that the HIC values in Positions B and C decreased with the use of the thinner frame. Figure 9 (b) shows that the RDC values did not appear to change significantly. Therefore, it was found that the thinner frame in the bench-end partition improved safety.

![Fig. 7 Comparison of HIC and RDC](image)

![Fig. 8 Comparison of SIVH](image)

3.2.2 Countermeasures for passenger in position C

This section considers countermeasures for passengers in Position C. The impact on reducing the severity of injury to passengers using handrails was investigated.

Dummy models were seated on a longitudinal seat model. One initial seating position (Position C with handrail (Fig. 10(a))) and three initial seating postures (Forward, Forward 10 mm and Right 10 degree), Positions A and C (Fig. 10(b)) and Positions A and C with handrail (Fig. 10(c)) as shown in Fig. 10, were used, which comprised five conditions.

Figure 11 shows the comparison of HIC and RDC for Position C w/ and w/o handrail. The HIC values for Position C decreased progressively with the use of handrails.
for all seating postures. The RDC values did not appear to change significantly in any condition. It was found that adding a handrail improved safety.

The above-mentioned results demonstrate that the HIC for Position C progressively decreased with the use of handrails. This paragraph discusses the reasons leading to this outcome. Figure 12 shows Secondary impact velocity and position of the head on collision. The SIVH in position C with handrail was lower than that without handrail. The position of the dummy’s head on collision in Position C in the presence of handrails was more flexible than that in the absence of handrails. The inner parts of the partition were reinforced using a steel frame. Therefore, the stiffness of the partition was found to vary by position. These were the reasons why HIC in position C with the handrail was lower than without a handrail.

The severity of injury to the heads of passengers depended on secondary impact velocity and the area with which they collided. Therefore, there is the possibility that the handrail does not have much effect on reducing the severity of injury if the position of the head on collision, in the presence of handrails, is harder than the position on collision in the absence of handrails.

Figure 13 illustrates that both HIC and RDC in Positions A and C also decreased with the application of handrails. Figure 14 (a) shows that the dummy’s shoulder in Position C collided with another dummy’s right thorax. Figure 14 (b) depicts that the dummy’s behavior in Position C was changed because of the handrail. It was observed that at an identical acceleration pulse the HIC and RDC of the dummies depended on the handrail.
The conditions of the acceleration pulse were limited in this study. Therefore, further studies are needed using numerical simulation in order to enhance the safety of passengers seated on longitudinal seating.

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Authors

Kazuma NAKAI, Dr. Eng.
Senior Researcher, Ergonomics Laboratory, Human Science Division
Research Areas: Mechanical dynamics, Ergonomics, Crashworthiness, Human Dynamics

Tomohiro OKINO
Senior Researcher, Vehicle & Bogie Parts Strength Laboratory, Vehicle Structure Technology Division
Research Areas: Crashworthiness, Car Body Strength

Daisuke SUZUKI, Dr. Eng.
Senior Researcher, Ergonomics Laboratory, Human Science Division
Research Areas: Safety Ergonomics, Human Factors

Junichi TAKANO
Assistant Senior Researcher, Vehicle & Bogie Parts Strength Laboratory, Vehicle Structure Technology Division
Research Areas: Crashworthiness, Fire Safety

Shota ENAMI
Researcher, Ergonomics Laboratory, Human Science Division
Research Areas: Ergonomics, Crashworthiness