

An Estimation of Behaviour and Severity of Injury to Rail Passengers Occupying Longitudinal Seats in the Event of Collision

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Abstract In order to enhance safety rail passengers occupying longitudinal seats, the risk to occupants in the event of collision were identified by means of a sled test. Taking the hypothesis of a train colliding with something in the direction of travel, the behaviour and injuries of the ES-2 dummy on a longitudinal seat were estimated. The results of the test made it clear that the collision position and the secondary impact velocity of the dummy's head to the bench-end partition depends on the initial position of the dummy in the same input acceleration. The head injury to the passenger next to the bench-end partition is low and the head and thorax injury to the passenger far from the bench-end partition are low because of the leaning occupant. These findings show that the high risk initial positions of an occupant on longitudinal seating are passengers seated second-furthest and third-furthest away from the bench-end partition.

Keywords railway, passenger, safety, injury, sled test, longitudinal seat, impact biomechanics.

I. INTRODUCTION

In the unlikely event of a train collision, on-board safety features play a critical role in protecting its occupants. In order to design interior passive safety features aimed at reducing occupant injury levels, it is necessary to examine the probability of such injuries occurring. In recent years, a significant research has been conducted on vehicle interior crashworthiness [1-3]. Collision scenarios in these studies are shown in Fig. 1. Fig. 1 (a) shows the occupant's head and knees impacting the seat back of the seat in front of the occupant. Fig. 1 (b) shows the occupant's back of the head impacting the back of the seat on which they are sitting. Fig. 1 (c) shows the occupant's thorax and abdomen impacting the fixed table in front of the occupant. Previous research tends to be focused solely on transverse seating arrangements. The UK's Railway Group Standards (RGS) [4] sets the framework for structural crashworthiness design and it is considered to be one of the most advanced specifications of its type. This standard provides the sled test method for evaluating the injury to passengers seated on transverse seating. On the other hand, there is no standard for evaluating the injury to passengers occupying longitudinal seats. After all, an evaluation method for passengers occupying longitudinal seats has not been established yet. Commuter trains in Japan mainly use longitudinal seating, as do some metro trains in European countries. Therefore, it is necessary to enhance safety of occupants on longitudinal seating.

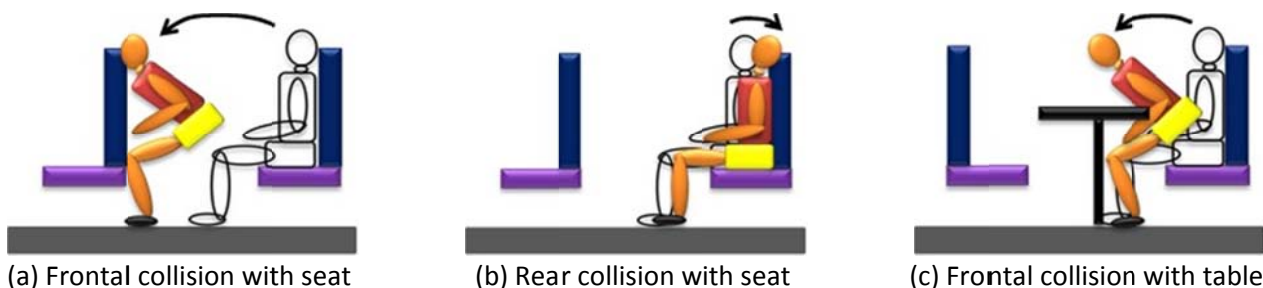


Fig. 1. Collision scenarios in previous studies.

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In order to enhance safety of passengers occupying longitudinal seats, it is important to accurately identify the risk to occupants in the event of a train collision. In previous research [5], data on the injuries of passengers were categorized by occupant posture (i.e. standing or sitting) in the event of a commuter train collision. An accident occurred in Japan when a following train collided with a preceding train at approximately 30 km/h. This research indicated that the dividers, which are arranged in end of the longitudinal seating, cause chest injuries to passengers sitting adjacent to them. The effects of the type of divider on the severity of chest injuries were examined. However, since then there has been little research on this area in Japan, so it is difficult to grasp the risk of these occupants by static technique. In order to identify the risk to longitudinal seat occupants, passenger behaviour and severity of injury in the event of a train collision were examined by means of a sled test and numerical simulation [5-6].

The risk to occupants depends on the direction of train collision. A review of severe railway accidents in Japan over the past 25 years (1989–2014) has indicated that over 80% of the 76 accidents identified were head-on collisions or collision with an obstacle in the direction of travel [7-8], as shown in Table I. A serious railway accident is defined as an incident where either there have been at least 10 casualties and/or at least 10 cars have derailed. In previous research [1-3] and the RGS standard [4], train collisions in the direction of travel is assumed. Thus, this paper focuses on collisions occurring in the direction of travel.

From previous research [5], there is a high probability that the injuries to the passengers occupying longitudinal seats are caused by the dividers and the partition wall which are arranged at the end of longitudinal seating. Moreover, passenger behaviour and severity of injury depends on position of occupants on longitudinal seating. In order to identify the position of high risk to an occupant, passenger behaviour and the severity of injury were estimated by a sled test. It was found that the high risk initial positions of an occupant on longitudinal seating were passengers seated second-furthest and third-furthest away from the bench-end partition.

TABLE I
NUMBER OF SERIOUS RAILWAY ACCIDENTS (APRIL 1989–MARCH 2014)

Category of accident	Number
<u>Collision from direction of vehicle</u>	63
<i>Collision with a car/lorry on a level-crossing</i>	32
<i>Head-on collision</i>	20
<i>Collision with obstacles</i>	7
<i>Collision with a Buffer stop</i>	4
<u>Other</u>	13
Total	76

II. METHODS

In order to identify the risk to passengers occupying longitudinal seats in the event of a train collision in the direction of travel, passenger behaviour and the severity of injury were estimated using a sled test experimental program to replicate eight scenarios. An ES-2 dummy was chosen to represent seated passengers. This type of dummy was selected because of its capability for side-impact injury assessment which is consistent with the scenario being studied. A collision in the direction of travel involving a railway vehicle with a longitudinal seating arrangement would create a situation whereby the occupant would suffer a lateral impact. Interior components used included a floor section, a longitudinal seat and a bench-end partition (Height: 1,500 mm, width: 1,000 mm, thick: 1.6 mm, material: SS400) on the sled, as seen in Fig. 2. The dynamic acceleration pulse in the direction of the travel was used as the input condition.

Characteristics of bench-end partition

The existing components, for example, the divider or the partition wall in the train, were not used as a bench-end partition in the sled test. In general, the inner parts of the existing components were reinforced by a structural element. Hence the stiffness of the components varies by position, as seen in Fig. 3. Furthermore, the severity of injury to the occupants depends on which area they collide with. A single plate which was not

reinforced by the structural element was chosen as a bench-end partition due to the focus on the relation between occupant behaviour and injury in this paper. A plate size (Height: 1,500 mm, width: 1,000 mm) larger than the dummy on the sagittal plane was chosen. The plate's material was SS400 which has been used as one of the structural elements of the existing components. The plate thickness of 1.6 mm was decided by the outcome of the impact test, as shown below.

In order to choose a bench-end partition with stiffness close to existing component's stiffness, it is necessary to grasp the stiffness of the existing components. An experiment to obtain the stiffness was conducted by striking the existing components with an impactor representing the occupant's head (Diameter: 165mm, mass: 6.8kg). Fig. 4 shows the appearance of partition wall experiment. The head impactor collided with the hard position and the soft position of the partition wall respectively. The impact test was designed so it would replicate the same level velocity (approximately 5 m/s) as the velocity of the dummy's head during the sled test. A reaction force with respect to impact load was calculated with the multiplication of the impactor mass by the acceleration which is measured by the accelerometer in the impactor. The velocity of the impactor and a warp stroke of the partition wall at collision were calculated with the displacement which is measured by the magnescale on the impactor. The sampling time of the acceleration and the displacement was 10 microseconds and they were filtered by the CFC1000 which is used to calculate the Head Injury Criterion. The recorded data are plotted respectively on a graph (Fig. 5), where the horizontal axis represents the warp stroke and the vertical axis the reaction force. This figure shows that the force increases according to increased stroke in a range from an appearance to the maximum force. The maximum slopes of the hard position and the soft position were approximately 1100 N/mm and 350 N/mm, respectively. This slope was defined as the stiffness in this paper. The reaction force increases at the collision according to increased slope.

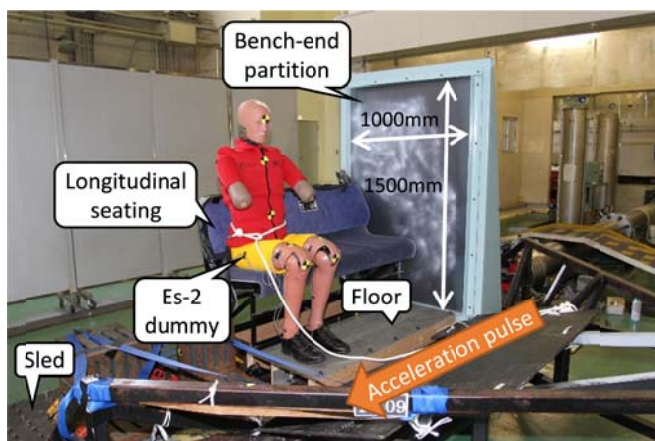
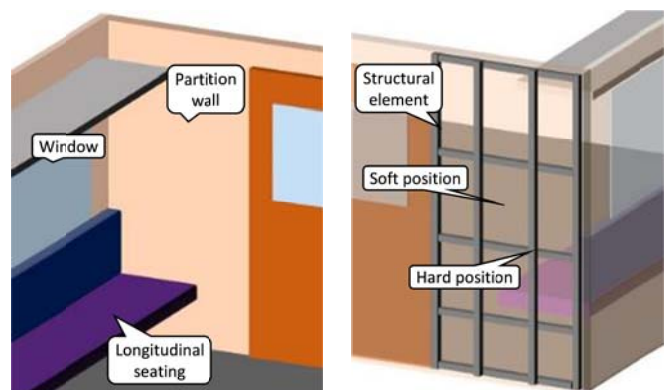


Fig. 2. Layout on the sled.



(a) Existing components. (b) Inner part of partition.
Fig. 3. Appearance of existing components in the train.

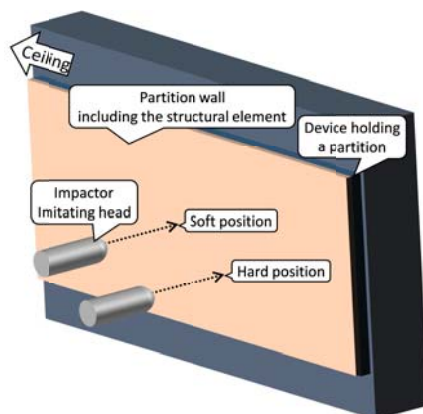


Fig. 4. Appearance of partition wall experiment.

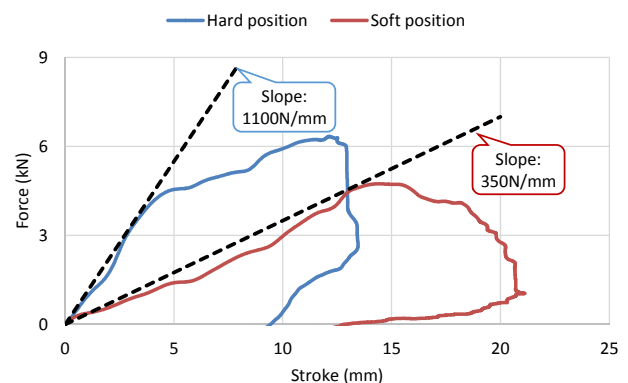


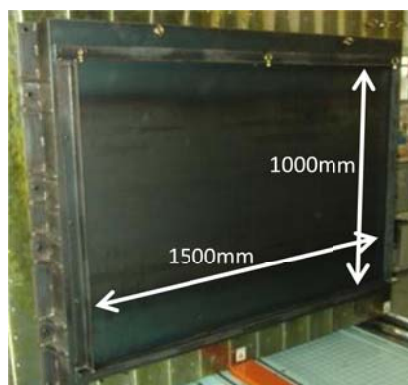
Fig. 5. Result of partition wall experiment.

In addition, the stiffness of the SS400 plates (Thick: 4.5mm, 3.2mm, 1.6mm) were also measured by conducting the same experiment respectively, as seen in Fig. 6. The impactor colliding position was close to the collision location of the dummy's head during the sled test. The stiffness was approximately 2250 N/mm, 1200 N/mm and 400 N/mm, respectively. Figure 7 compares the stiffness of the partition wall and the SS400. It shows that SS400 (Thick: 3.2mm) is close to the partition wall (hard) and that SS400 (Thick: 1.6mm) is also close to the partition wall (soft). In order to avoid measurement failure during the sled test due to mechanical failure of the dummy, SS400 (Height: 1,500 mm, width: 1,000 mm, thick: 1.6 mm, material: SS400) was chosen as a bench-end partition.

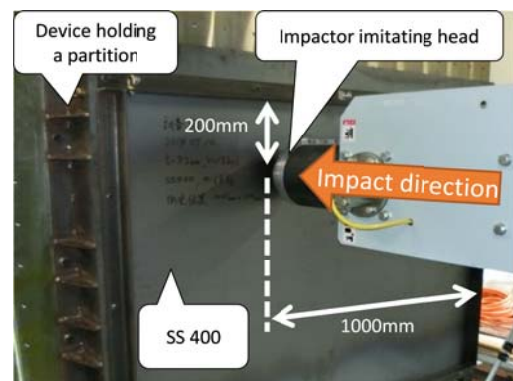
Test conditions

As mentioned above, the sled test method for passengers occupying longitudinal seats has not been established. The RGS [4] provides the dynamic acceleration pulse corridor of the sled test for evaluating the injury to passengers seated on transverse seating. Referring to the corridor, five types of dynamic acceleration pulse as shown in Fig. 8 (a) were used as input test conditions. The acceleration pulse of 7G is close to the pulse as defined in the RGS (Fig. 8 (b)). It was difficult to reproduce the plateau of the pulse due to the efficiency of the testing equipment. However, the velocity of the pulse 7G (ΔV) is consistent to the ΔV of the corridor as defined in the RGS, as shown in Fig. 8 (c).

A dummy was seated on a longitudinal seat. Three initial seating positions (Position A, Position B, Position C) as shown in figure Fig. 9 were used, making a total of eight test scenarios (Table II). Test no. 1-5 were chosen to identify the high risk initial position. Test no. 6-8 were chosen to grasp the risk to passengers far from the bench-end partition, which is unique to a railway vehicle with a longitudinal seating arrangement.



(a) Condition of holding SS400.



(b) Impactor colliding position.

Fig. 6. Appearance of SS400 experiment.

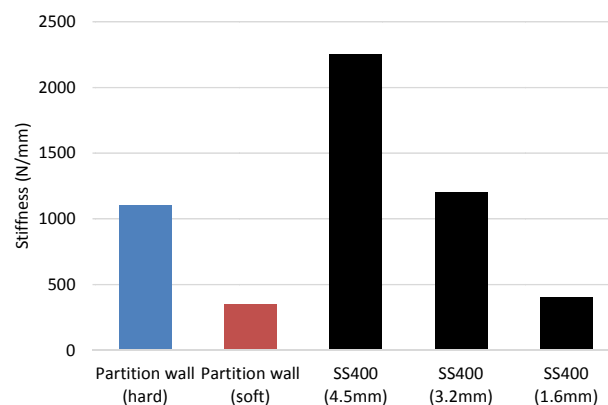
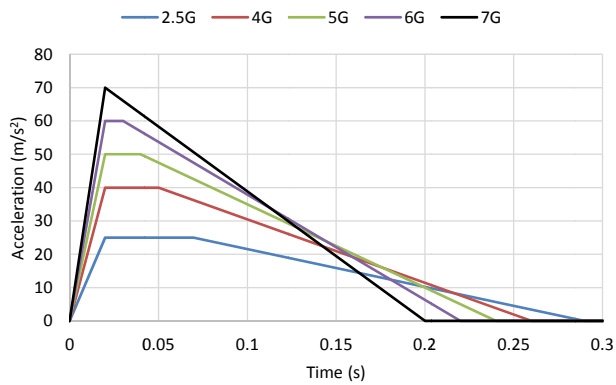
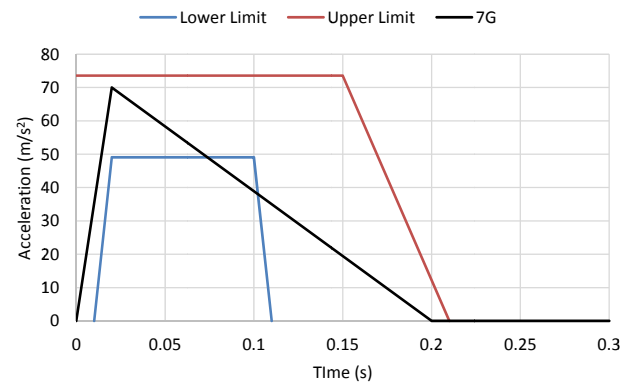


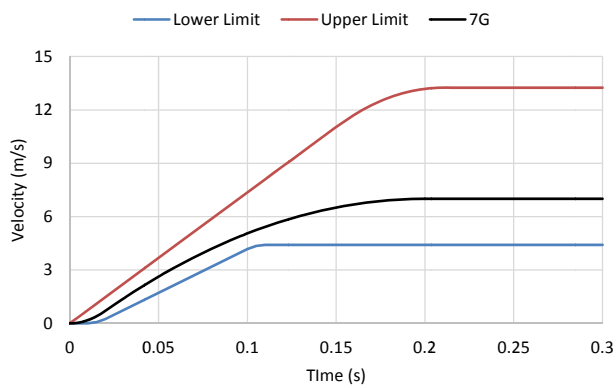
Fig. 7. Comparison of stiffness.



(a) Target of acceleration pulse.

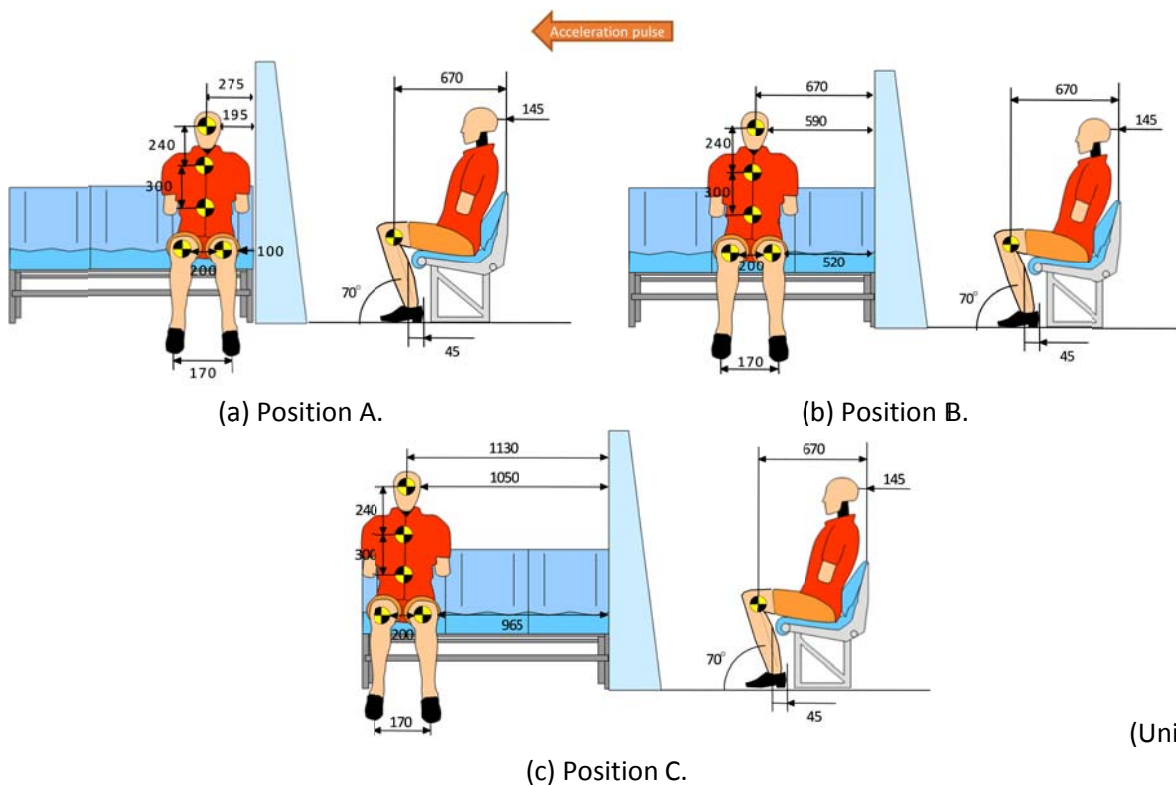


(b) Relation acceleration between pulse 7G and RGS corridor.



(c) Relation DeltaV between pulse 7G and RGS corridor.

Fig. 8. Test conditions of input pulse.



(Unit: mm)

Fig. 9. Test conditions of initial position.

Dummy behaviour

Dummy behaviour was evaluated using the collision position to bench-end partition of dummy's head from the floor, and the secondary impact velocity to bench-end partition of dummy's head (SIVH). The kinematic motion of the dummy was measured using two high-speed cameras. The video image was recorded from the ground and on the sled respectively. The sampling time was 1 millisecond. The relative velocity of the dummy's head to the sled (RV) was calculated from the video image. The relative dummy's head coordinate to the sled was calculated from the recorded coordinate of the dummy's head and the sled. This relative coordinate was differentiated to obtain the RV in the direction of input acceleration. The RV data of the test no. 3 are plotted on a graph (Fig. 10). 1 millisecond before the RV shows a sharp decline which was defined as the secondary impact time in this paper. The SIVH was defined as the RV at the secondary impact.

Injury criteria of dummy

The injury criteria of dummies on longitudinal seating has not been established. Therefore, in this paper the dummy injuries were evaluated using the HPC (Head Performance Criterion) and the RDC (Rib Deflection Criterion) which that have been used extensively for assessing the safety of automotive occupants [9]. 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 were 1,000 mm and 42 mm respectively. In this paper, these values were used as a limit values. The HPC calculation method is the same as HIC (Head Injury Criterion) calculation method, 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.

TABLE II
TEST SCENARIO

Test no.	Acceleration pulse	Initial position
1	Pulse 7G	Position A
2	Pulse 7G	Position B
3	Pulse 7G	Position C
4	Pulse 5G	Position B
5	Pulse 5G	Position C
6	Pulse 6G	Position C
7	Pulse 4G	Position C
8	Pulse 2.5G	Position C

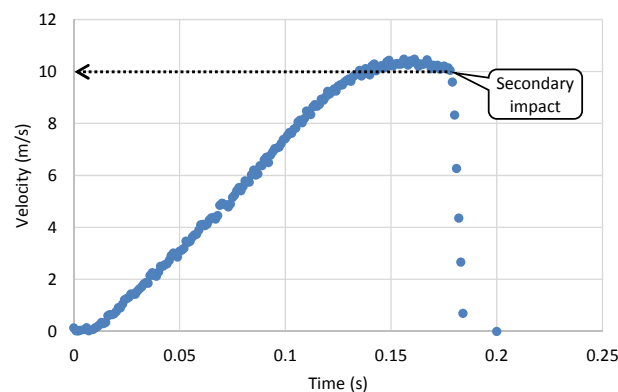


Fig. 10. Time history of RV (test no.3).

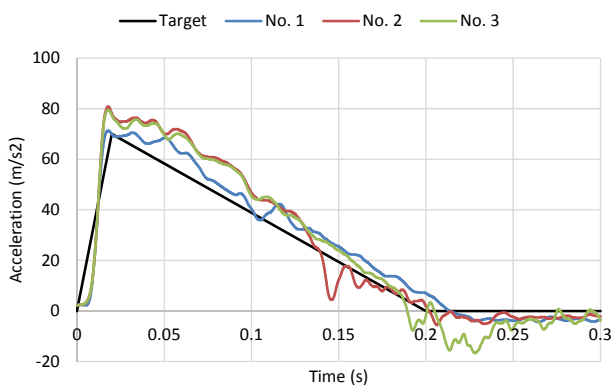
III. RESULTS

Reproducibility of acceleration pulse

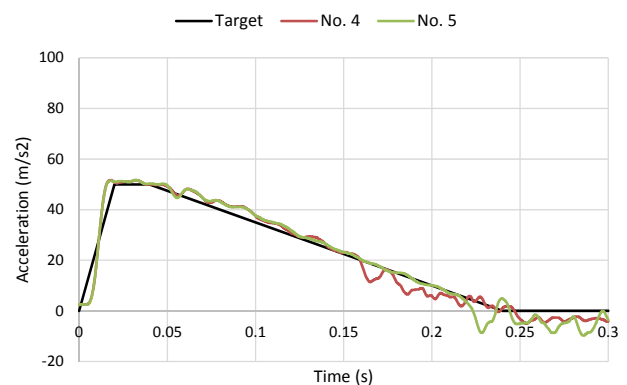
Figure 11 (a) and (b) compare the target and sled acceleration pulses. Figure 11 (c) and (d) compare the target and sled DeltaV pulses. This figure shows that the maximum sled acceleration and DeltaV with pulse 7G are slightly higher than the target and that the sled acceleration and DeltaV pulse with pulse 5G almost corresponds with the target pulse.

Evaluation of behaviour

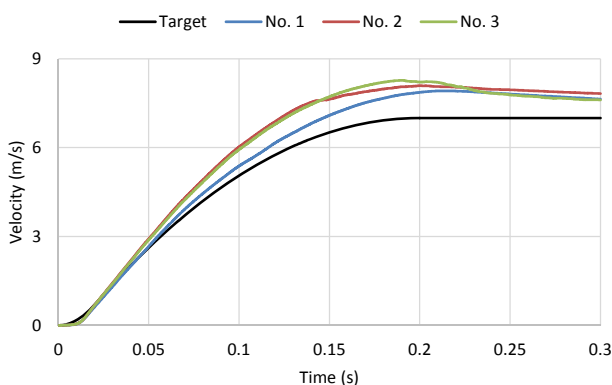
The ES-2 dummy was seated on a longitudinal seat as an initial position (Fig. 12). The movement of the dummy at secondary impact with pulse 7G and pulse 5G is shown in Figs 13 and 14 (Test no. 1-5). Figure 13 (a) shows that the dummy's head collided with the partition after the dummy's thorax collided with the partition at position A. Figure 13 (b) shows that the dummy's head collided with the partition after the dummy's shoulder collided with the partition. Figure 13 (c) and Figure 14 show that the dummy's head collided with the partition before the other dummy's regions collided with the partition. This type of behaviour was also shown at position C (Test no. 6-8). Table III shows the collision position from the floor and the SIVH according to test conditions. The collision position with pulse 7G and 5G are shown in Figs 15 (Test no. 1-5). This figure shows that the collision position decreases according to the distance away from the bench-end partition. The SIVH with pulse 7G and 5G are shown in Figs 16 (Test no. 1-5). This figure shows that the SIVH with pulse 7G increases according to the distance away from the bench-end partition. However, the SIVH with pulse 5G decreases according to the distance away from the bench-end partition. It was found that the collision position and the SIVH depends on the initial position in the same acceleration pulse.



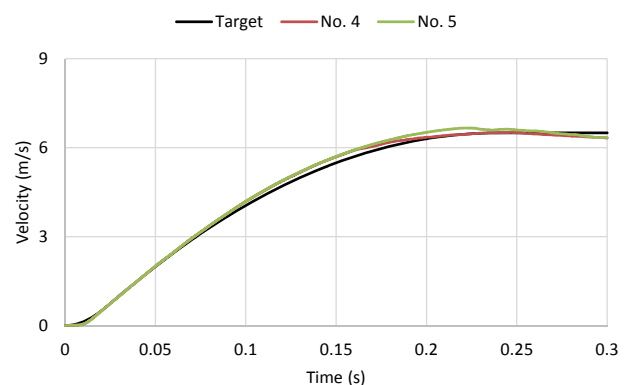
(a) Acceleration with Pulse 7G.



(b) Acceleration with Pulse 5G.



(c) DeltaV with Pulse 7G.



(d) DeltaV with Pulse 5G.

Fig. 11. Time history of target acceleration pulse, sled acceleration pulse and DeltaV.



(a) Position A.



(b) Position B.



(c) Position C.

Fig. 12. Initial position.



(a) Position A.



(b) Position B.



(c) Position C.

Fig. 13. Behaviour of dummy at secondary impact with pulse 7G.



(a) Position B.



(b) Position C.

Fig. 14. Behaviour of dummy at secondary impact with pulse 5G.

TABLE III
TEST RESULTS

Test no.	Acceleration pulse	Initial position	Behaviour		Injury	
			Collision Position (mm)	SIVH (m/s)	HPC Limit: 1000	RDC (mm) Limit: 42
1	Pulse 7G	Position A	1235	4.1	271	24
2	Pulse 7G	Position B	1240	9.7	1576	40
3	Pulse 7G	Position C	1155	10.0	1467	18
4	Pulse 5G	Position B	1190	8.2	905	18
5	Pulse 5G	Position C	1040	6.5	714	5
6	Pulse 6G	Position C	1153	9.0	967	13
7	Pulse 4G	Position C	963	4.4	369	5
8	Pulse 2.5G	Position C	720	0.2	21	3

Evaluation of injury

The severity of the HPC and the RDC are also shown in Table III. This table shows that the HPC values vary according to the SIVH. The HPC values vs. SIVH at position C are shown in Fig. 17. This figure shows that the HPC increases progressively according to increased SIVH. For identifying the high risk initial position from the point of view of head and thorax injuries, the quotient of HPC/1000 and RDC/42 with pulse 7G and 5G are shown in Fig. 18. This figure shows that the HPC values of the dummy at position A are low and that the RDC values of the dummy at position C are low.

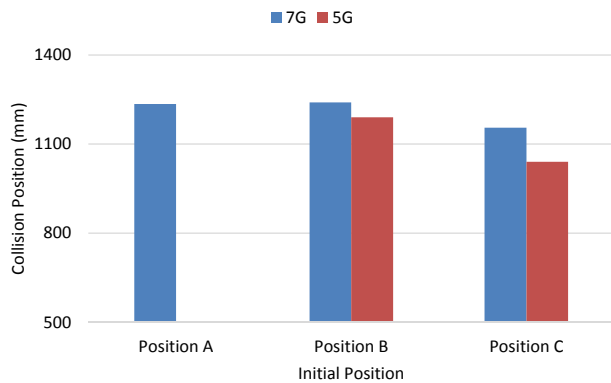


Fig. 15. Collision Position.

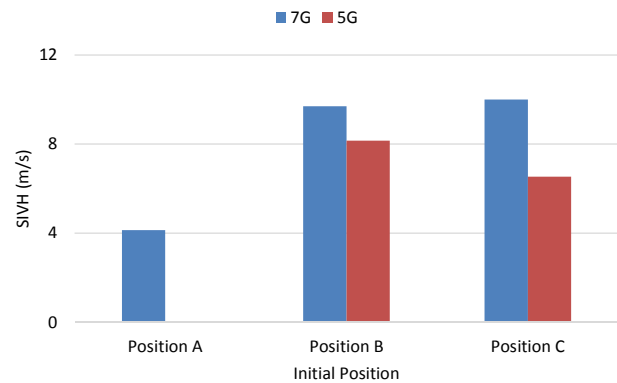


Fig. 16. SIVH.

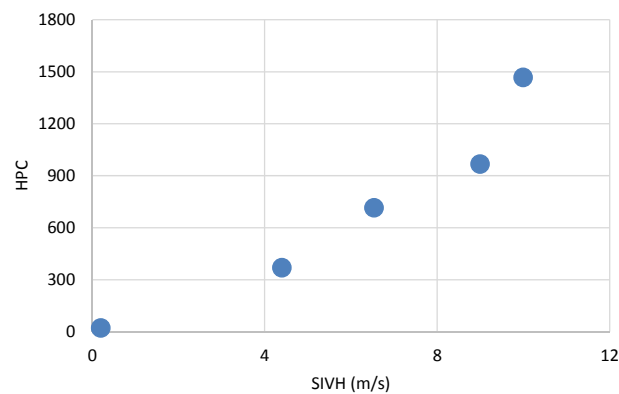
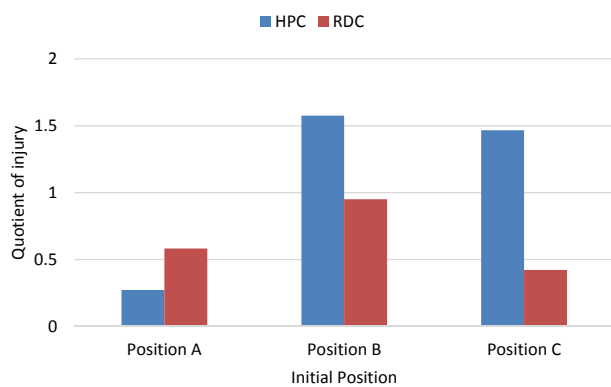
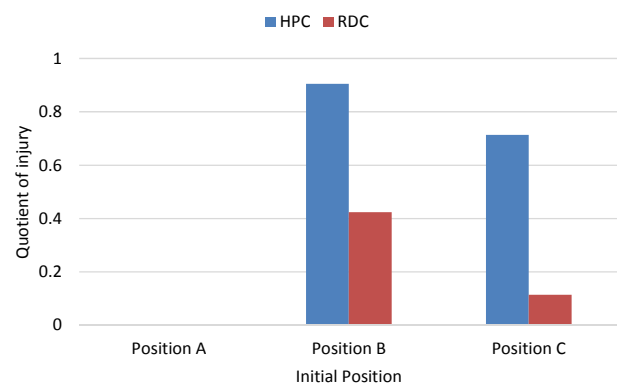


Fig. 17. HPC vs. SIVH at position C.



(a) Pulse 7G.



(b) Pulse 5G.

Fig. 18. Quotient of injury.

IV. DISCUSSION

The results set out above have demonstrated that the HPC values are low at position A and the RDC values are low at position C. This section discusses the reasons behind this outcome. In addition, the contribution of friction between the dummy and the seat to the results is discussed.

HPC

The HPC increases progressively according to increased SIVH. The DeltaV and RV with pulse 7G and 5G are shown in Figs 19 and 20. These figures show that the DeltaV is different from the RV. RV is the relative velocity of the dummy's head to the sled and DeltaV is the sled velocity from the ground. RV is higher than DeltaV due to the leaning dummy at secondary impact, as seen in Fig. 21. BV is the velocity of dummy's head in the direction of acceleration pulse from the ground. BV depends on the dummy behaviour. RV equal DeltaV if BV is zero due to without the leaning dummy at secondary impact. RV and the DeltaV with pulse 7G and 5G are shown in Fig. 22. Figure 22 (a) shows that the dummy's head collided with the partition before the DeltaV is high at position A with pulse 7G. Therefore, the SIVH at position A was low. The SIVH at position B was lower than the SIVH at position C. However, the HPC values at position B were higher than the values at position C. The time band of the HPC at position B (4.7 millisecond) was longer than the time band of the HPC at position C (2.2 millisecond). The difference of the time band leads to the difference in HPC values. Figure 22 (b) shows that the dummy's head collided with the partition after the RV is low at position C with pulse 5G. Therefore, the SIVH at position C was low. It was found that the severity of head injury to the passenger next to the bench-end partition is low and that the severity of head injury to the passenger far from the bench-end partition is low because of the leaning occupant.

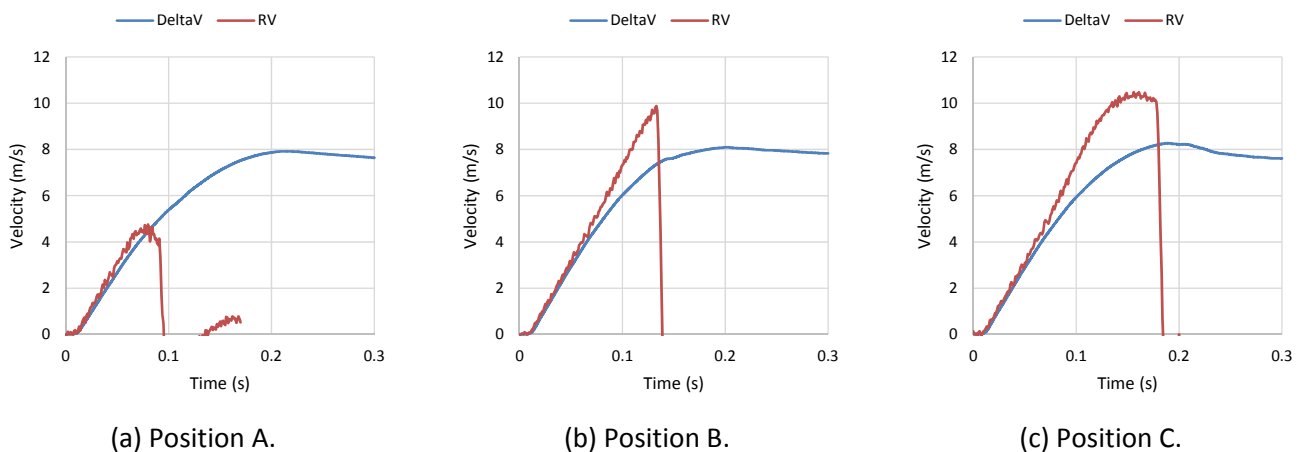


Fig. 19. Time history of DeltaV and RV with pulse 7G.

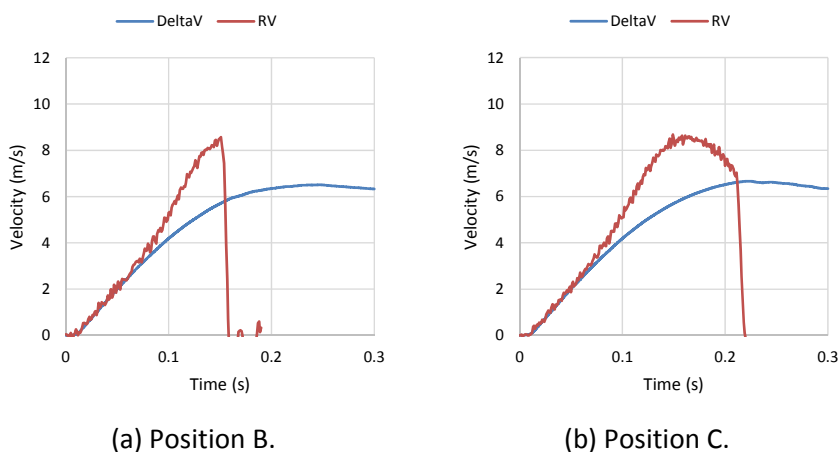


Fig. 20. Time history of DeltaV and RV with pulse 5G.

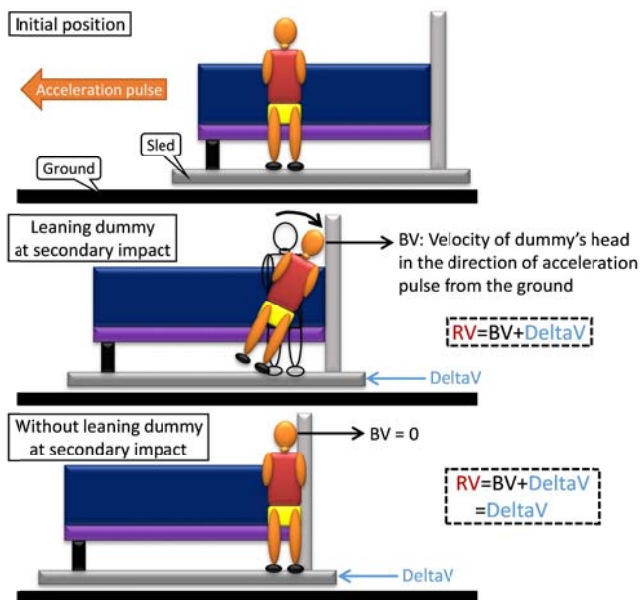
RDC

The RDC values were low with pulse 7G and 5G at position C. It was found that the dummy thorax did not collide with the partition strongly because the leaning dummy (Fig. 13 (c), Fig. 14 (b)) led to a small RDC. There are two reasons why the RDC values at position B are higher than the RDC values at position A with pulse 7G. The first reason is that the secondary impact velocity of the dummy thorax at position B to the partition was higher than the secondary impact velocity of the dummy thorax at position A to the partition. The rib deflection of the dummy at position A and position B is shown in Fig. 23. This figure shows that lower rib of the dummy at position B was very low. Therefore, the second reason is that the secondary impact was concentrated on the upper rib and middle rib of the dummy at position B. It was found that the severity of thorax injury to the passenger far from the end partition is low because of the leaning occupant.

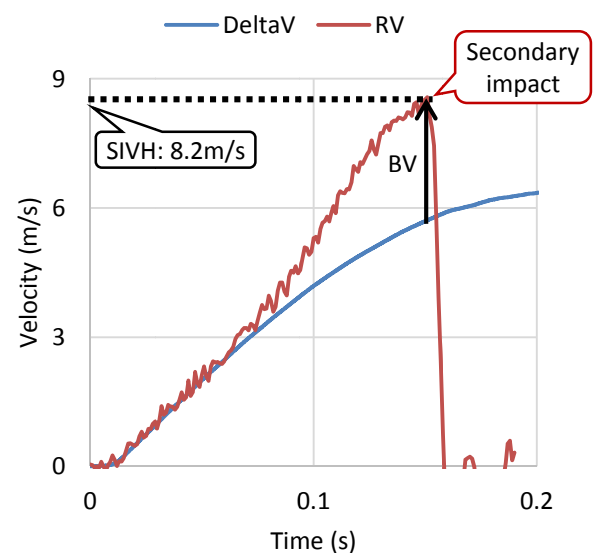
Contribution of friction

It is considered that the severity of injury to the dummy was very dependent on its behaviour, which in turn is dependent on the friction between the dummy and the longitudinal seat. This friction effect also depends on the initial position. It seems that the RDC values of dummy at position C increases according to the decrease in friction. However, it seems that the HPC and RDC values of dummy at position A do not depend on the friction.

These discussion suggest that the high risk initial positions are those sitting second-furthest and third-furthest away from the bench-end partition, even when friction is taken into account.

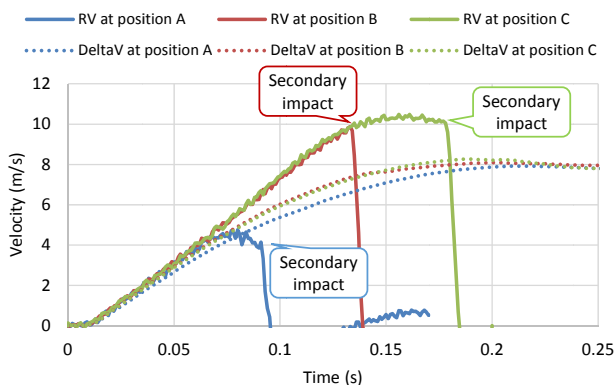


(a) Behaviour of dummy at secondary impact.

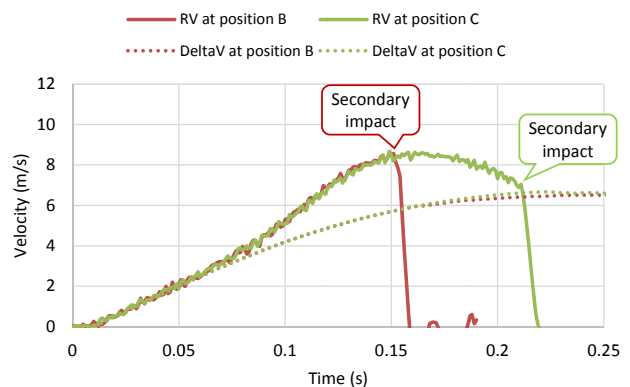


(b) Time history of DeltaV and RV (test no.4).

Fig. 21. Concept of RV.



(a) Pulse 7G.



(b) Pulse 5G.

Fig. 22. Time history of RV and DeltaV.

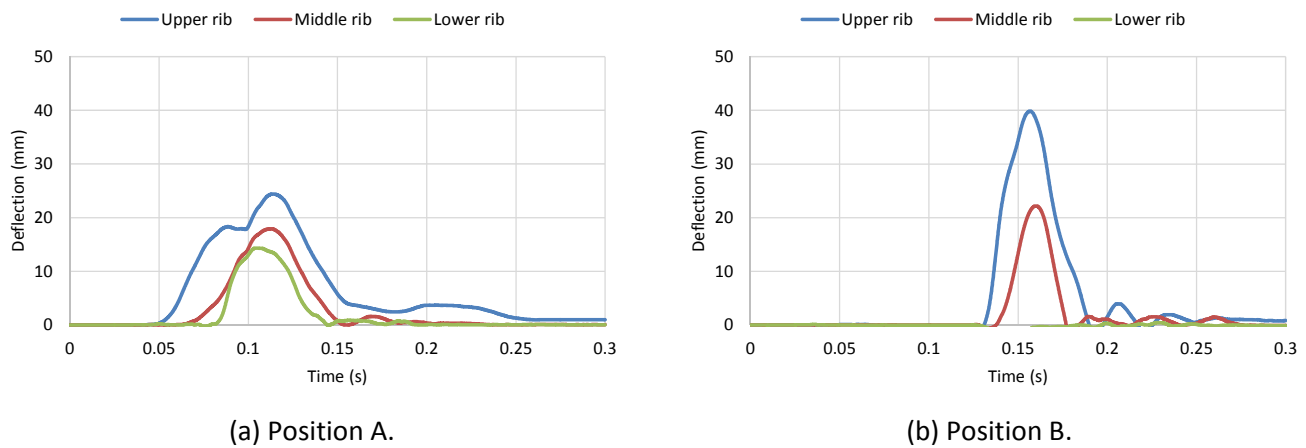


Fig. 23. Time history of rib deflection with pulse 7G.

V. CONCLUSIONS

This study focuses on passengers seated on longitudinal seating in the event of a train collision in the direction of travel, for which the evaluation method has not been established. In order to identify the high risk initial position of an occupant, the occupant behaviour and the severity of injury to a dummy were quantified in eight unique test scenarios, which include the same level of dynamic acceleration pulse which is provided by the RGS. It was found that the severity of injury to a dummy was highly dependent on its behaviour, which in turn was strongly dependent on the initial position on the longitudinal seat. It is evident from the data that the high risk initial positions of an occupant on longitudinal seating were those seated second-furthest and third-furthest away from the bench-end partition. The authors suggest that an occupant in these initial positions should be evaluated in the event of a train collision in the direction of travel in order to enhance the safety of occupants on longitudinal seating.

The condition of the bench-end partition stiffness, the acceleration pulse and the number of the occupants were limited in this paper. Therefore further studies are needed by means of a sled test and numerical simulation in order to enhance the safety of occupants on longitudinal seating.

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