Evaluation Method for Crashworthiness Using Integrated Value of Deceleration of Railway Vehicles Showing High Correlation with Degree of Passenger Injury

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While standards for crashworthiness of railway vehicles have been defined in Europe and the U.S., there is no standard in Japan. Therefore, it is important to establish an evaluation method for crashworthiness of railway vehicles in Japan. The authors carried out finite element analyses under various conditions based on the statistical analysis of serious level-crossing accidents. We evaluated the mean decelerations (conforming to European standard), the maximum decelerations (U.S. standard) and integrated values of the deceleration, which are obtained from impact deceleration waveforms in the passenger area. We also performed finite element analyses of dummy’s behavior and injury values using these deceleration waveforms as input. We examined the correlation between these evaluation results and dummy’s injury values. As a result, we confirmed that the integrated values of the deceleration of the passenger area had the highest correlation with the dummy’s injury values.

**Key words:** crashworthiness, passenger injury, level-crossing accident, finite element analysis

1. Introduction

Railway car body structures capable of mitigating passenger and crew injuries in the event of a collision accident are important for safety. The Japanese design standards for car body structures, however, do not necessarily assume accidents involving collisions and have not clarified collision scenarios and indices for evaluating vehicle crashworthiness. On the other hand, European countries and the U.S. have design standards for vehicle crashworthiness (EN15227 and 49 CFR Part 238). These standards, however, are designed specifically to each country’s railway system, past accidents and other local requirements. For example, in Europe, in-car safety evaluation methods for collision analyses are based on the mean impact deceleration of the car body used as an index [1]. In the U.S. however, the maximum impact deceleration is used [2], and a limit value is defined for each index.

In Japan, the indices for evaluating crashworthiness of railway vehicles are not specified, although some railway operators have adopted their own unique design methods considering past level-crossing accident cases, etc. Consequently, while it is important to improve crash safety in the event of a collision accident in a way which matches the operating conditions each operator, European railway vehicle manufacturers with a global market share may take the lead in mainstreaming European standards by including them in ISO standards in the future. Therefore, it is extremely important to study the design standards for vehicle crashworthiness and develop a unified approach in Japan.

After defining the collision conditions based on statistical survey results of serious level-crossing accidents in Japan, this study conducted FE (finite element) analyses that simulated level-crossing accidents by changing conditions such as the collision speed, the collision obstacle and the mutual relative positions, and calculated the impact deceleration waveforms of the car body in each condition. We obtained the integrated deceleration value as well as the mean deceleration (European standard evaluation index) and the maximum deceleration (U.S. standard evaluation index). In addition, we conducted FE analyses of passenger behavior on transverse seats by using the same deceleration waveforms as input. These analyses allowed us to calculate the injury values of each dummy and verify the correlation between the three evaluation indices and a dummy’s injury values. From the results, we confirmed that the integrated deceleration value had a higher correlation with the injury value of the dummy than the existing European and U.S. evaluation indices. In addition, we presented the evaluation indices and their limit values for vehicle crashworthiness in Japan.

2. Statistical survey of level-crossing accidents

To consider the factors that increase the damage to the occupants (including the crew and passengers), we defined level-crossing accidents with 5 or more injuries or 1 or more on-board fatalities as serious level-crossing accidents. Fifty-four serious level-crossing accidents occurred during the 30 fiscal years from 1987 to 2016. Figure 1 (a) and (b) show the distribution of estimated collision speeds and the breakdown of collision obstacles for these accidents, respectively. Figure 1 (c) shows the relationship between the number of casualties and the estimated collision speed, with the whole divided into two categories according to the mass of each collision obstacle. Compact cars, light trucks, and tractors were classified as relatively lightweight obstacles, and trucks, trailers, dump-trucks, and buses were classified as relatively heavy obstacles. The approximate estimated collision speed was calculated by using the distance from the brake start point of the train to the level-crossing and the train speed at the start of braking (based on the crew’s verbal report), and by assuming that the deceleration was constant. The Railway Safety Database of Railway Technology Promotion Center at the RTRI was used for the general condition survey of each accident,
and if the Railway Accidents Analysis Report of the Japan Transport Safety Board included the estimated collision speed, that value was quoted.

For serious level-crossing accidents, the estimated collision speeds were widely distributed from 15 to 117 km/h. The class with the highest number of cases was 51 to 60 km/h, and the mean estimated collision speed was 57 km/h. Trucks were the most frequent obstacle, accounting for 31% of the total, whereas trailers and dump-trucks accounted for 20% and 19%, respectively: goods vehicles therefore formed the obstacle in 70% of these collisions. Compact cars accounted for 15% of the collision obstacle. No clear correlation was found between the estimated collision speed and the number of casualties.

Serious level-crossing accidents that caused relatively significant injury to occupants were not concentrated in a high collision speed range and were widely distributed with a mean of 57 km/h, while relatively heavy goods vehicles accounted for 70% of the collision obstacles. Since no clear correlation exists between the collision speed and the number of casualties, other factors than the collision speed or the mass of the collision obstacle were considered to be factors which increased levels of injury to occupants. Figure 1 (c) shows two accidents with a high number of casualties despite an estimated collision speed of less than 30 km/h, and these were characterized by a significantly large mass of the collision obstacle and a large number of passengers. Another two accidents had relatively few casualties even though the collision obstacles were relatively heavy with an estimated collision speed of around 100 km/h. These were characterized by an offset collision where only part of the front of the train collided with the obstacle. In this way, in addition to the collision speed and obstacle mass, the relative positional relationship between the train and obstacle in a collision and the occupancy rate and passenger posture (e.g. standing/sitting) may affect the degree of damage to the occupants. However, we could not evaluate these quantitatively because detailed information on all accidents could not be obtained and many conditions differed from accident to accident.

3. FE analysis of level-crossing accidents under various conditions

3.1 Level-crossing accident analysis model and analysis conditions

Figure 2 shows a level-crossing accident analysis model. The train model is a one-body model with a standard stainless steel car body structure. Its total mass was set to 30,700 kg, the mass of interior items and underfloor equipment was distributed evenly to the underframe, and the mass and inertia moment of bogie were given to be in a position equivalent to its center of gravity. The bogie mass point was constrained in its degree of freedom, except translational motion in the train running direction. This train model achieved analytical accuracy of impact behaviors by considering the strain rate dependence on the mechanical properties of materials.

Based on the results of Section 2, as the collision obstacle, a dump-truck was selected because it was considered to be the most sturdy goods vehicle with the highest car body strength. The dump-truck model has a reference total mass of 22,000 kg (including a load of 11,000 kg [maximum loading capacity]) and is constructed with shell elements based on an element pitch of 50 mm for the main structural section. For the tire-ground contact surface, the friction coefficient was set to 0.4. The load was constructed of 150 mm square solid elements so that, assuming dirt and sand, they would be pressed against the side of the truck bed by the inertia force in the collision, and the behavior of some of the load jumping out of the truck bed could be reproduced, while the calculation time remained within a practical range. For the vertical positional relationship between the train and the dump-truck, the reference was defined in the position where the distance between the underframe of the train and the underside of the truck bed is 355 mm. The reference speed of the train model is defined as 54 km/h from the past statistical results. The dump-truck is assumed to be stationary.
In the statistical results of serious level-crossing accidents in Section 2, the collision speeds were widely distributed with a mean of 57 km/h without being concentrated in a high speed range, whereas relatively heavy goods vehicles accounted for 70% of the collision obstacles. The relative position of the train and the collision obstacle was also assumed to be important factor affecting the degree of damage to passengers. Thus, to simulate various collision conditions found in the serious level-crossing accidents, we varied the following conditions and calculated the deceleration waveforms of the car body (3 locations in total: center of the car body, front bolster, and rear bolster) from the collision start time to approx. 300 ms: collision speed (20 to 120 km/h); collision angle (5 conditions: 90° [reference], ±5°, ±10°); horizontal collision position (5 conditions in Fig. 3: position where the center line of the train coincides with the position of the load center, body center, cabin center, 1/2 lap, or 1/4 lap); vertical collision position (4 conditions in Fig. 4: reference position [green], 177 mm lower than the reference [blue], 354 mm lower than the reference [purple], and 512 mm lower than the reference [red]; green and blue were the overriding conditions, where the truck bed floor was above the underframe of the train); and the dump load mass (0 to 13,750 kg). The total number of car body deceleration waveforms from these level-crossing accident analyses was 222.

3.2 Injury analysis model of passengers in transverse seats

Figure 5 shows an injury analysis model of passengers on transverse seats. Inputting the impact deceleration waveform into this model made it possible to calculate the injury value of each part (e.g., head, chest, and femur) of the dummy model resulting from it colliding with the seat in front of it. We evaluated the femur load in the single-seat condition, which was most likely to cause serious injury, based on a previous study [3]. The femur load is a femur injury index, which indicates more serious injury as the value increases.

A total of 222 car body deceleration waveforms calculated in the previous section were input to calculate the dummy model’s femur load (hereinafter “dummy injury value”) with this model.

3.3 Example of FE analysis results

As collision behavior examples, this section shows the results of level-crossing accident analysis in the reference condition (collision speed: 54 km/h; load mass: 11,000 kg; collision angle: 90°; horizontal position: center of the load in Fig. 3; vertical position: green in Fig. 4). Figure 6 shows the time histories of the train speed at the center position of the car body and the dump-truck speed at the center position of the load. Figure 7 shows the time histories of the contact force between the train and the dump-truck, and impact deceleration at the center of the train car body. The contact force was...
filtered using a CFC60 filter, widely used in the automobile industry, and the impact deceleration was filtered using a 50 Hz lowpass filter in accordance with the U.S. standards. The time when the train and the dump-truck came into contact was defined as time zero.

These figures show the following: the force of the collision caused the train to slow down and the dump-truck to accelerate, and the impact deceleration of the train reached its maximum (about 7 G) approx. 40 ms after the collision; the train and dump-truck had the same speed of 36 km/h in about 100 ms, when the amount of deformation of the train and dump-truck was the maximum. After that, the train decelerated and the dump-truck accelerated due to a spring-back effect. Since collision position was closer to the rear of the dump-truck than the center of gravity of the entire dump-truck (i.e., towards the left in Fig. 3), the dump-truck rotated counter-clockwise. Therefore, the contact force did not drop to 0 within 300 ms, and the train continued to decelerate.

From the deceleration waveforms in Fig. 7, the mean deceleration based on the European standard was calculated to be 3.8 G (see Section 4 for the calculation method), and the maximum deceleration using the U.S. standard was calculated to be 7.0 G. Using this deceleration waveform as the input, the femur load was calculated to be 4.3 kN by using the passenger injury analysis model shown in Fig. 5.

4. Evaluation method for crashworthiness

4.1 Method of study

We obtained the following three evaluation indices, (1) to (3), from the 222 car body deceleration waveforms from the level-crossing accident analysis shown in Section 3.1, and also obtained the dummy injury values (4) using the passenger injury analysis model shown in Section 3.2. At that time, we verified the behavior from the collision time to about 300 ms at a sampling frequency of 10 kHz.

(1) Mean deceleration (under the European standard)
(2) Maximum deceleration (under the U.S. standard)
(3) Integrated deceleration value (proposed index)
(4) Dummy injury value (femur load)

According to the European standards, the mean deceleration is defined as the mean value of the period from when the contact force on the train exceeds 0 to the time when it next falls again to 0, but if an excessive time elapses before the force falls to 0 then the time for it to fall to 10% of the maximum force should be used; our study adopted the latter in all conditions (Note: the European standard was revised in 2020, and the method for calculating the mean deceleration was also revised. The study using the new method is currently under consideration). When calculating the integrated deceleration value in (3), in all cases, we defined the train - dump-truck contact start time as time 0 and used the following three integration times:

TP_1: Until the time \( t_{\text{imp}} \) when the contact force falls to 10% of the maximum force.

TP_2: Until the time \( t_{\text{imp}} \) when the dummy model collided with the front seat and the femur load value reaches the maximum.

TP_3: Until the time \( t_{\text{imp}} \) when the double integrated value of the deceleration of the car body reaches 440 mm.

TP_1 is an evaluation time equivalent to that of the European standards. TP_2 was set assuming that the femur load of the dummy model was at the maximum as a result of the kinetic behavior of the dummy model and the seat by the car body deceleration up to \( t_{\text{imp}} \), and it was expected that the correlation with the dummy injury value would be the highest. However, obtaining \( t_{\text{imp}} \) requires a passenger injury analysis as well as a collision analysis between the train and obstacle, thus it is unlikely to be the crashworthiness evaluation index of the car body structure. For TP_3, assuming that the passengers maintain the uniform motion even after the train crashes, the amount of passenger movement relative to the floor and the double integrated value of the deceleration of the car body are considered to be almost equivalent. Hereby, the double integrated value of the deceleration for TP_3 was set to 440 mm, the distance from the tip of the cushion to the back of the front seat back in the passenger injury analysis model (Fig. 5). In other words, the time \( t_{\text{imp}} \) is an estimate of the time \( t_{\text{imp}} \) when the dummy model collides with the front seat.

4.2 Proposal of evaluation method for crashworthiness

The dummy injury value of (4) in the previous section is taken on the vertical axis, and the mean deceleration of (1) (European standards) and the maximum deceleration of (2) (US standards) are taken on the horizontal axis; they are shown in Fig. 8 (a) and (b), respectively. Figure 9 (a), (b), and (c) show the integrated deceleration values for TP_1, TP_2 and TP_3 of (3), which are given on each horizontal axis. Each figure includes a linear approximation line (blue line), an exponential approximation curve (red line), and each coefficient of determination (R^2 value), in addition, a dashed line that indicates 10 kN, which is the reference value of the dummy injury value (femur load).

Figure 8 shows that, for the mean deceleration (European standards), the coefficient of determination of linear approximation is larger (0.82) and it correlates well with the dummy injury value. Meanwhile, for the maximum deceleration (U.S. standards), the coefficient of determination of exponential approximation is larger, and it was clarified that it is not as good as the mean deceleration although a certain degree of correlation (0.66) is observed.

Figure 9 (a) shows that, for the integral of deceleration (integration time: TP_1), the coefficient of determination of linear approximation is larger (0.90) and it has a good correlation with the dummy injury value. Figure 9 (b) shows that, for the integral of deceleration (TP_2), the coefficient of determination of exponential approximation is larger (0.96) and strongly correlates with the dummy injury value. The integral of deceleration (TP_3) was larger for the coefficient of determination of exponential approximation (0.93), similar to the result at TP_2 (Fig. 9 (c)). As a result, it correlates highly with the dummy injury value in the order of integration times TP_2 > TP_3 > TP_1. The result that the highest correlation was found at TP_2 is as expected above, and it is unlikely to be an evaluation index because of the need to carry out a passenger injury analysis. However, the coefficient of determination 0.96 is suggested as the maximum value (target value) of the correlation with the dummy injury value, and the coefficient of determination 0.93 of the integral of deceleration (TP_3) can be judged to be close to the target value.

Table 1 summarizes the above results in order of good correlation with the dummy injury value. According to Table 1, the integral of deceleration (TP_3) is the optimal evaluation index for crashworthiness in Japan when the injury degree of passengers in transverse seats is taken into account.

Meanwhile, the maximum deceleration (U.S. standards) is not recommended as an evaluation index because of its low correlation with the dummy injury value. The mean deceleration (European standards) and the integral of deceleration (TP_1) exhibited a relatively good correlation. The European standards are adopted not only in Europe but also in many countries such as Asian countries; therefore, in the future, they may be included in global standards.
like ISO. Although these two evaluation indices are not as good as the integral of deceleration (TP_3), they are also recommended as Japanese standards because they have a relatively good correlation with the dummy injury value. However, since they have a lower correlation with the dummy injury value than the optimum evaluation index, the safety factor needs to be higher, and therefore the vehicle cost is expected to increase.

So far, we have investigated the evaluation indices for crashworthiness of car body structure in Japan, but when they and their limit values are determined in Japan, a wide discussion needs to be organized among related ministries, railway operators, vehicle manufacturers and other parties. At that time, the findings obtained in this study will be very useful. We propose to proceed with the discussion based on the two crashworthiness evaluation methods in Table 2 considering the high correlation with the dummy injury value and the global standardization in the near future. We determined the limit values from the reference values of the dummy injury values in Fig. 9.

The reason for selecting Proposal 1 is that it has the strongest correlation with the dummy injury value (coefficient of determination 0.93) among the conditions examined in this study. In addition, the advantages listed include the fact that only the deceleration waveform of the car body is required without the train-obstacle contact force waveform required for the European standards and that the evaluation time can be varied depending on the distance between the seats (calculated as 440 mm in this study). Proposal 1 may be optimal in Japan, where there is no standard for crashworthiness. However, keeping in mind the global standardization such as future migration of the European standards to ISO, Proposal 2 presents an evaluation index close to the European standards because the

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**Table 1** Comparison result of correlation with dummy injury value

| Evaluation indices                  | Coefficient of determination ($R^2$) | Note                  |
|-------------------------------------|--------------------------------------|-----------------------|
| Integral of deceleration (TP_2)     | 0.96                                 | Need injury analysis  |
| Integral of deceleration (TP_3)     | 0.93                                 |                       |
| Integral of deceleration (TP_1)     | 0.90                                 |                       |
| Mean deceleration                   | 0.82                                 | European standard     |
| Maximum deceleration                | 0.66                                 | U.S. standard         |
evaluation time is the same and exhibits a coefficient of determination of 0.90, which has a good enough correlation with the dummy injury value.

Table 2 Proposal of evaluation method for crashworthiness

| Evaluation index                     | Limit value |
|--------------------------------------|-------------|
| Proposal 1 - Integral of deceleration (TP_3) | 7.5 m/s     |
| Proposal 2 - Integral of deceleration (TP_1) | 11 m/s      |

5. Conclusions

In order to improve passenger safety in the event of collision accidents, this paper examined crashworthiness evaluation methods that are available for railway vehicle designs and that suit local conditions of railway transportation in Japan. This study performed collision analyses under various level-crossing accident conditions matching conditions in Japan, and examined the processing method of the impact deceleration waveforms generated in a car body, which has a high correlation with the injury value of passengers on transverse seats.

As a result, we confirmed that the proposed integrated deceleration value has a higher correlation with the passenger injury value than the existing European and U.S. evaluation indices. Considering the high correlation with passenger injury value and global standardization in the near future, this study proposed the integrated deceleration values with two different integration times, TP_3 (period of time until double integrated value of car body deceleration reaches the value depending on the distance between the seats) or TP_1 (evaluation time equivalent to the European standards), as crashworthiness evaluation indices, and their limit values.

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