Vol. 10, No. 2, pp. 21-26, December 2011

INTERNATIONAL
JOURNAL OF SAFETY
www.kosos.or.kr

Danger Estimation with HIC and Risk Curve in Passengers Falls from Running Rail Cars

Toshiko Nakagawa

Department of Electrical and Electronic Engineering, Tokyo City University, 1-28-1, Tamazutsumi, Setagaya-ku, Tokyo 158-8557, Japan

(Received October 6, 2011; Accepted December 15, 2011)

Abstract : In 2001, an independent official board was constituted in Japan to investigate aircraft and railway accidents. In the past 10 years, many accidents and serious incidents have been investigated and these official reports were published by the board, on which the author had sat for 9 years as boarding member. In the interim, there were several train disasters which mocked our trust in railways and also many apparent trivial incidents. In recent years, serious incidents, which a door of running rail cars opens suddenly with some trouble, happen 2 or 3 times in a year. For the past 10 years, such incidents have happened 14 times and 13 cases of them were closed by the board mentioned above. In these 13 cases, no one fell off the rail car, so that the death toll was none luckily. In this paper, these 13 serious incidents are picked up among all the reports published by the board and outlined using some tables. Especially, fall accidents of passengers are discussed mainly from the view point of impact force and duration time. Then, the equation of HIC (Head Injury Criteria) and the risk curves in terms of the HIC are dealt with properly.

Key words : door- trouble, passengers' fall, rail-car, incident report by JTSB, impact force

1. Introduction

Japan's railway is considered to be one of the most reliable systems in the world, although there have been several cruel accidents in history. In fact, it is said that the death rate of a passenger in a train is much less than that of a person walking outside. Nobody is distraught with fears to death on travels by train. Some of passengers sleep defenselessly in a train seat; others lean on a door of carriage as if it were a firm wall.

In recent years, serious incidents that a door of running rail-cars opens suddenly with some trouble or malfunction happen 2 or 3 times in a year as shown in Fig. 1. The number of such incidents amounts to 14 since the constitution of the commission ARAIC (Aircraft and Railway Accidents Investigation Commission: This commission was reconstructed to JTSB (Japan Transport Safety Board) in 2009). Such incidents, which are categorized as "serious incident" in the board, are very dangerous because there is some possibility that a passenger fall out of the running rail-car.

*Corresponding author: nakagat@tcu.ac.jp

2. Serious incidents by door troubles

Table 1 shows a list of the above-mentioned serious incidents by door-troubles. This list consists of the data from the official reports [1]-[13], but it doesn't include many similar incidents at zero- speed or very low speed because of the regulations that JTSB (or ARAIC) does not deal with such cases.

The causes of the incidents are various. Some are by

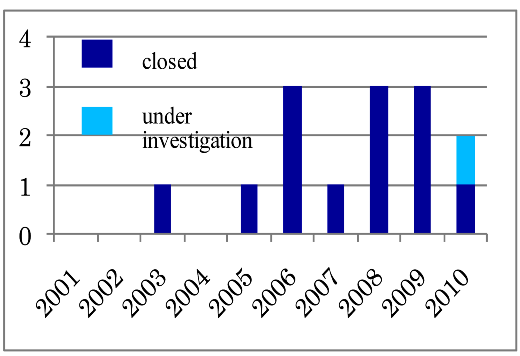

Fig. 1. The number of serious incidents by door troubles of railway cars.

Table 1. List of serious incidents by door-troubles of railway cars

Case No.	Date	Company	Estimated causes described in the JTSB (ARAIC) reports or other related factors
1[1]	2003 Nov. 4	Mountain Railway	Unsuitable Works (incorrectness in position for latch-attachment)
2[2]	2005 Aug. 16	Metro (urban)	Unsuitable Works (wrong size of lid attached on a short-circuit box)
3[3]	2006 Feb. 4	JR(A)*	Metal Fatigue (air pressure pipe under the car-body)
4[4]	2006 Mar. 11	Private-Railway (urban)	Deterioration of Insulation in the Connecter Box (ion migration by water drips)
5[5]	2006 Oct. 7	JR(B)*	Looseness of Attachment-Parts (fall of bolt-nuts from the car body)
6[6]	2007 May 28	JR(C)*	Unsuitable Works (incorrectness in soldering)
7[7]	2008 July 30	Private-Railway (urban)	Deterioration of Mechanics (unsmooth motion in a door switch)
8[8]	2008 Sept. 13	JR(B)*	Deterioration of Mechanics (unsmooth door motion by floor distortion with metal corrosion) Lack of Confirmation for Doors by Crews
9[9]	2008 Nov. 25	JR(C)*	Deterioration of Insulation and Unsuitable Works (short circuit at a motor-bearing and wear of shielded cable)
10[10]	2009 May 1	Private-Railway	Electro-Magnetic Interference (wrong actions in door mechanism)
11[11]	2009 Oct. 2	Private-Railway	Metal Fatigue (break of door-pin)
12[12]	2009 Dec. 5	JR(C)*	Metal Fatigue (fracture between a door cylinder and its link)
13[13]	2010 May. 29	JR(D)*	Deterioration of Mechanics (causes have not been complexly clarified so far)
14	2010 Oct. 29	JR(E)*	Under Investigation

JR(#)* : One of 6 Japan Railway Companies

(a)200% (b) 100%

Pictures by Ministry of Land, Infrastructure, Transport and Tourism, Japan (http://www.mlit.go.jp/sogoseisaku/transport/koukeika/h19censusgaiyou.htm)

Fig. 2. Rate of Congestion.

deteriorations in door-mechanism of opening or closing, others are from troubles of electric circuits for opening or closing doors. Some of these causes are not clear or suspected to be electro-magnetic noise from the surroundings. However, even if these causes are originated by mechanical or electrical matters, all of them will, in some sense, be related to human factors such as design principles of device, choice of materials, works for improving, mending, wiring or attachments and works for regular maintenance.

These incidents by door-troubles resulted in no injury by luck, because every train was not crowded. As for the rate of congestion, the definitions by the association of Japanese Private Railways are shown in

Fig. 2 and Table 2. In case that the rate is within 150% - 200%, it means that passengers stand, pressing together tightly.

Now from Table 1, three cases (2, 4 and 7) in the urban lines are picked up. In Tab.3, each congestion rate for these three cases is calculated with “Full complement of the train” and “the number of passengers in the train when the incident happened” and it is compared with the day’s maximum [14] of the congestion rate for each line. If these three cases occurred under the condition shown in Fig. 2, they would be cruel accidents with many passengers’ falls. Actually, these three lines have 167%, 154% and 127% of congestion rate as the maximum respectively as shown in Table 3.

3. Impact force on free falls

With regard to fall accidents, Table 4 shows us useful information. A fall with parachute or a fall onto a safety-net tends to have long time-duration and small impact acceleration. On the contrary, the time duration

Table 2. Definitions of rate congestion

Rate of Congestion	Definitions
100% (Full Complement)	Passengers can have a seat, hold a strap or catch a door-pole
150%	Passengers stand shoulder to shoulder
200%	Passengers feel oppression each other
250%	Passengers will scarcely budge each other in a railway car

Definitions by Association of Japanese Private Railways (http://www.mintetsu.or.jp/knowledge/term/96.html)

Table 3. Rate of congestion of train

Case No.	Full Complement	The Number of Passengers	Rate of Congestion	Maximum Rate [14] of Congestion
2	1420	100	7 %	167 %
4	700	200	29 %	154 %
7	1420	500	35 %	127 %

Table 4. Impact acceleration and its time duration for each event [15]

Event	Acceleration	Time Duration
Landing by parachute	3~4G	0.1~0.2[s]
Fall onto a safety net	20G	0.1[s]
Fall onto snowy slope	200G	0.015~0.03[s]
Fall onto hard surface (Fall-height ; 1.8 m)	250G	0.007[s]

Table 5. Calculations of HIC referring to the data [16]

Case	Fall Height [m]	Impact Acceleration [G]	Impact Velocity [m/s]	Time Duration [s]	HIC by Eq.(5)
(a)	13.5	159 (169*)	15 (16*)	0.0098	3124
(b)	6.9	85 (91*)	11 (12*)	0.013	865
(c)	3.6	58 (128*)	8 (8*)	0.0067	174
(d)	4.5	56 (58*)	9 (9*)	0.0166	387
(e)	3.0	36 (39*)	7 (8*)	0.02	153

in a fall onto a very hard surface tends to become impulsive, so that the impact force at landing will be very large. This tendency matches the law of conservation of momentum.

The actual data of free falls which is selected from the reference [16] is shown in Table 5. (But as described later, the data in the last column of Table 5 is not from the reference [16] but the values calculated in terms of Eq. (5).

Table 6. Critical height based on HIC-1000

Material	Critical Height [m]			
	Depth; 16 cm	Depth; 23 cm	Depth; 31 cm	Depth; 23 cm (firmed)
Wood chips	2.1 @	3.0 @	3.3 @	3.0 #
Sand(fine)	1.5 @	1.5 @	2.7 @	1.5 #
Sand(coarse)	1.5 #	1.5 #	1.8 #	1.2 #
Gravel(fine)	1.8 @	2.1 @	3.0 @	1.8 #
Gravel(coarse)	1.5 #	1.5 #	1.8 #	1.5 #

@: Source; Reference[17]
(http://www.cpsc.gov/CPSCPUB/PUBS/323.HTML)
: Source; Independent Test at Pennsylvania State University in accordance with ASTM F1292
(http://www.habitat-systems.com/files/kit/Surfacing_ Guide.pdf

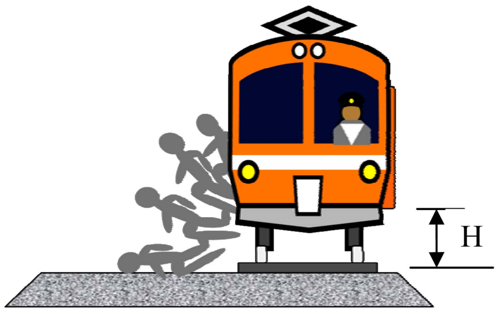

Fig. 3. Cross section of rail car.

See hereinafter.)

Table 5 consists of five cases of free fall accidents ((a) - (e)), in which all of five victims survived.

Viewing every fall accident from dynamics, the following equations for the vertical axis(y) are introduced based on the impulse momentum theorem.

Eq. (5) is a well-known criterion of head injury as HIC and is useful in evaluating the magnitude of impact to a human body especially to a head.

$$mgH = \frac{1}{2}mv_{y_1}^2 \therefore v_{y_1} = \sqrt{2gH} \qquad (t = t_1) \tag{1}$$

$$v_{y2} = 0 \qquad (t = t_2 = t_1 + \Delta t) \tag{2}$$

$$\int_{t_1}^{t_2} F_y dt \cong \bar{F}_y \Delta t = \Delta p_y = m(v_{y2} - v_{y1}) \tag{3}$$

$$\begin{aligned} &\therefore \bar{F}_y \Delta t = m\sqrt{2gH} \qquad \therefore \bar{a}_y \Delta t = \sqrt{2gH} \\ &\therefore \bar{a}_y = \sqrt{2gH}/\Delta t \quad [m/s^2] \\ &\therefore \bar{A}_y \cong \sqrt{2H/g}/\Delta t \quad [G] \end{aligned} \tag{4}$$

$$HIC \equiv (t_2 - t_1)\left[\frac{1}{(t_2 - t_1)}\int_{t_2}^{t_1} A_y(t)dt\right]^{2.5} \quad (5)$$

$$\cong \Delta t[\overline{A_y}]^{2.5} = \Delta t(2H/g)^{2.5/2}/(\Delta t)^{2.5} = (2H/g)^{1.25}/\Delta t^{1.5} \quad (6)$$

where, $\Delta t(=t_2 - t_1)$ duration time denotes [s] of impact, g is 9.8[m/s^2], H denotes fall height [m], v_{y1} and v_{y2} are the preceding and the following velocities to the impact respectively, Δp_y is a variation of momentum, F_y is a impact force, a_y is an accelaration of impact, A_y is its G - value and (-) denotes an average of each variable.

To verify the procedure by Eq.(1)- Eq.(6), the impact velocity (v_y) and the impact average acceleration ($\overline{A_y}$) are calculated on trial by means of Eq. (1) and Eq. (4) respectively, substituting the data of each value of fall-height in the second column and each value of time-duration in the 5-th column of Table 5.

As a result, it was found that these calculated values (*) in the 4-th and 3-d column of Table 5 are almost correspondent to the values in the 4-th column and the 3-d column of Table 5 respectively. Hence, deciding that the procedure by Eq. (1)-Eq. (6) is proper, the values of HIC are calculated by Eq. (5). (See the last column of Table 5.)

4. Impact force of a fall by door troubles

As Japanese railway systems are very reliable, many people use railways almost every day to go to and from their office or school. Therefore in Japan, commuter trains are jammed with passengers very much. Sometimes passengers can't open out their newspapers in rail cars and some passengers can hardly budge being sandwiched between another passengers and a carriage door.

Supposing that the door suddenly opens by some troubles under such conditions, many passengers will be thrown out from the carriage as shown in Fig. 3.

By the way, Table 6 shows the data [7] of "critical height" at various playground surface released by CPSC (United States Consumer Product Safety Commission) and Pennsylvania State University. "Critical height" is the fall height for which the HIC becomes 1000.

As for the coarse gravel similar to ballast in railways, if the depth of the gravel is 23 cm -31 cm, which is almost same to the required depth of ballast in the regulation of Japanese Railway, the critical height is 1.5-1.8 m by Table 6. This height is larger than the floor height H (H is about 1.2 m in ordinary railway cars) shown in Fig. 3. However, it doesn't always mean that a fall from a rail car is safe, because the trains are not

Table 7. Evaluation of safety in case of Passengers fall

Case No.	V0 [km/h] ([m/s]) (actual data)	Acceleration[G] (calculation) 7 msec / 15 msec / 20 msec	HIC (calculation) 7 msec / 15 msec / 20 msec
1	11 (3)	83	432
		39	144
		29	86
2	40 (11)	176	278
		82	926
		62	556
3	115 (32)	473	33035
		220	11011
		166	6607
4	50 (14)	216	4685
		101	1562
		76	937
5	120 (34)	500	38322
		234	12778
		175	7664
6	No data		
7	10 #1 (3)	83	432
		39	144
		29	86
8	No data		
9	40-50#2 (11-14)	202	3977
		94	1326
		71	795
10	10 #1 (3)	83	432
		39	144
		29	86
11	60#2 (17)	257	7283
		120	2428
		90	1457
12	70#2 (20)	300	10652
		140	3551
		105	2130
13	60#2 (17)	257	7283
		120	2428
		90	1457

#1; Velocity estimated as low speed at a start or stop

#2; Velocity estimated or supposed by the reports [9, 11, 12 and 13]. In this calculation, the data is for 13m/s.

Ballast: Case1, Case3-6, Case8-13. Concrete: Case2, Case7.

Table 8. Definitions of AIS's Classes

Class in AIS	Definitions
AIS1	Minor Injury
AIS2	Medium Injury
AIS3	Serious Injury
AIS4	Critical Injury
AIS5	Dying
AIS6	Death

fixed on the ground like playground equipment and in addition they have kinetic energy corresponding to their running velocity.

If the train runs with some speed (v_0), the impact force which the passengers thrown from the moving train receive will be much more. Then, Eq. (7) – Eq. (11) on another axis(x) of the moving direction must be added to the procedure by Eq. (1) – Eq. (6) on the vertical axis(y). As a result, Eq. (5) of HIC is modified to Eq. (11).

$$v_{x1} = v_0 \qquad (t = t_1) \tag{7}$$

$$v_{x2} = 0 \qquad (t = t_2) \tag{8}$$

$$\begin{aligned} &\int_{t_1}^{t_2} F_x dt = \bar{F}_x \Delta t = \Delta p_x = m(v_{x_2} - v_{x_1}) \\ &\therefore \bar{F}_x \Delta t = m v_0 \qquad \therefore \bar{a}_x \Delta t \cong v_0 \\ &\therefore \bar{a}_x \cong v_0 / \Delta t \quad [m/s^2] \\ &\therefore \bar{A}_x \cong v_0 / (g \Delta t) \qquad [G] \end{aligned} \tag{9}$$

$$\begin{aligned} &\therefore A = \sqrt{\bar{A}_x^2} + \sqrt{\bar{A}_y^2} = \sqrt{v_0^2/g^2 + 2H/g} / \Delta t \\ &HIC = (t_2 - t_1)\left[\frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} A(t) dt\right]^{2.5} \end{aligned} \tag{10}$$

$$\begin{aligned} &= \Delta t [\bar{A}]^{2.5} = \Delta t (v_0^2/g^2 + 2H/g)^{2.5/2} / (\Delta t)^{2.5} \\ &= (v_0^2/g^2 + 2H/g)^{1.25} / \Delta t^{1.5} \end{aligned} \tag{11}$$

From Eq. (10) and Eq. (11), the values of impact acceleration at landing and the values of HIC are calculated for 11 cases in Table 1 respectively as shown in Table 7. In these calculations, the time duration is chosen 7 msec, 15 msec or 20 msec, because, referring Table 4, we supposed that the time duration is between almost 7msec-30msec in free fall onto a common surface which is neither too hard nor too soft. In addition, the risk curves P_1-P_6, which are known as Expand Prasad/Mertz Curve, are calculated by Eq. (12) – Eq. (17) in terms of the HIC. The values of P_1-P_6 denote probability corresponding to AIS_1- AIS_6 respectively. (See Table 8 as to AIS)

$$P_1 = [1 + \exp((1.54 + 200/HIC) - 0.000650 \times HIC)]^{-1} \tag{12}$$

$$P_2 = [1 + \exp((2.49 + 200/HIC) - 0.00483 \times HIC)]^{-1} \tag{13}$$

$$P_3 = [1 + \exp((3.39 + 200/HIC) - 0.00372 \times HIC)]^{-1} \tag{14}$$

$$P_4 = [1 + \exp((4.90 + 200/HIC) - 0.00351 \times HIC)]^{-1} \tag{15}$$

$$P_5 = [1 + \exp((7.82 + 200/HIC) - 0.00429 \times HIC)]^{-1} \tag{16}$$

$$P_6 = [1 + \exp((12.2 + 200/HIC) - 0.00565 \times HIC)]^{-1} \tag{17}$$

where, the HIC value for "the time duration; 15msec" should be substituted to the above equations, because National Highway Traffic Safety Administration in USA adopts the "15msec".

5. Analysis of danger in fall accidents

As mentioned before, HIC 1000 is a critical value whether it is safe or not for head injury.

As shown in Table 7, some of the calculated HIC-values exceed 1000 extremely. With regard to the relation between AIS's level and such large values in HIC, the paper [18] takes some examples for children under 8 years old as target of study and gives us useful knowledge via various simulations. Two comments from the paper will be introduced here:

(a) Peak accelerations of as high as 350G and a duration of up to 3msec corresponding to HIC= 1700-2800

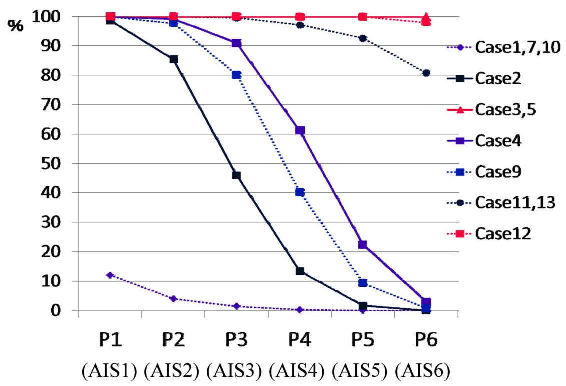

Fig. 4. Risk curve of the incidents (Case.1-5, 7, 9-13).

would produce only AIS 2 of injury.

(b) The survival limit for head impacts (AIS5 or greater) is estimated to be as high as 600G peak acceleration and a duration of up to 3 msec corresponding to up to 11000 in HIC.

As shown in Table 7, the HIC-values of the cases 11 and 13 are both 2428, which value is between 1700-2800 described in (a). As for the cases 4 and 9, the HIC values are 1562 and 1326 respectively, both of which are close to 1700 described in (a). From the values of P1- P6 for these 4 cases (Case 4,9,11,13) in Fig. 4, it is found that these values suggest the level of AIS2 as described in (a).

In addition, the HIC-values of the cases 3 and 5 are over 11000. The value-11000 is supposed to be AIS5 or grater as described in (b) and indeed Fig. 4 shows that the cases 3 and 5 reach 100% in P_6.(But as for the case 12, P6 is 99.9%, not 100%)

On the other hand, as far as the risk probability P_6 in Fig. 4 is concerned, it is considered that the cases 3, 5, and 12 will go to tragic accidents. However as these all cases occurred on the local lines without large congestion rate, death toll was none luckily.

6. Conclusion

This paper discusses 13 serious incidents which were reported officially by JTSB and arisen from door troubles, from the view point of safety in case of fall accidents.

If every incident occurred at a train with no velocity, it would be categorized as just a free fall accident. In such a case, as the fall height is 1.2 m or so, HIC value is fully smaller than the critical level (HIC=1000). However, if the train ran with some velocity and if the line had large congestion rate in urban area, such cases would really go to tragic accidents.

Serious incidents by door troubles have not decreased so far as shown in Fig.1 and may keep flattening out in number. In addition, the congestion rate will not be improved soon in Japan. Therefore tragic accidents of passengers' falls may occur at anytime and anywhere.

The causes of these incidents by door troubles are various as shown in Table 1. As mentioned in this paper, it is simply lucky that there has been no casualty in the serious incidents by door troubles so far. Therefore different types of countermeasures such as mechanical or electrical multi guard devices are strongly needed, in order not to open the doors absolutely when the train is running. In addition, steady and persistent efforts such as QC (quality control), Risk Management, Education or Technique Know-How Induction will be also required. There is not any shortcut in safety.

References

[1] ARAIC, RI2004-1, Ministry of Land, Infrastructure, Transport and Tourism, Oct. 2004.

[2] ARAIC, RI2007-1-1, Ministry of Land, Infrastructure, Transport and Tourism, Apr. 2007.

[3] ARAIC, RI2007-1-2, Ministry of Land, Infrastructure, Transport and Tourism, Apr. 2007.

[4] ARAIC, RI2008-2-2, Ministry of Land, Infrastructure, Transport and Tourism, Mar. 2008.

[5] ARAIC, RI2007-2-2, Ministry of Land, Infrastructure, Transport and Tourism, Sept. 2007.

[6] ARAIC, RI2008-1-1, Ministry of Land, Infrastructure, Transport and Tourism, Jan. 2008.

[7] JTSB, RI2009-2-2, Ministry of Land, Infrastructure, Transport and Tourism, Apr. 2009.

[8] JTSB, RI2009-1-1, Ministry of Land, Infrastructure, Transport and Tourism, Jan. 2009.

[9] JTSB, RI2009-4-2, Ministry of Land, Infrastructure, Transport and Tourism, Dec. 2009.

[10] JTSB, RI2010-1-1, Ministry of Land, Infrastructure, Transport and Tourism, June. 2010.

[11] JTSB, RI2010-2-1, Ministry of Land, Infrastructure, Transport and Tourism, Oct. 2010.

[12] JTSB, RI2010-2-2, Ministry of Land, Infrastructure, Transport and Tourism, Oct. 2010.

[13] JTSB, RI2011-2-1, Ministry of Land, Infrastructure, Transport and Tourism, June. 2011.

[14] Institution for Transport Policy Studies, Data book for Railway 2010, 2010, ISBN 978-4-903876-31-3

[15] Seki, Sakamoto, et al, Handbook of Human Tolerance Limitation, first ed. Asakura-press in Japan, 1990, ISBN 4-254-10086-8

[16] Richard G. Snyder, "State-of-the-Art: Human Impact Tolerance", SAE 700398, International Automotive Safety Conference Compendium, New York: Society of Automotive Engineers, May 1970.

[17] CPSC: Consumer Product Safety Commission, "Home Playground Safety Tips", CPSC-Document #323

[18] David R. Foust, *et al*., "Study of Human Impact Tolerance Using Investigations and Simulations of Free-Falls" SAE 770915, 1977