

# Effectiveness of a post-crash braking system in rear-end collisions in Japan

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**Abstract** - Twenty-eight percent of traffic accidents in Japan are rear-end collisions, and of these, 13% are multiple collisions (three or more vehicles and/or roadside objects). A post-crash braking system enables the driver to stop the vehicle in a short distance after a rear-end collision to prevent secondary collisions. In this study, the effectiveness of a post-crash braking system was examined using a drive recorder database. In 64% of rear-end collisions, the driver's braking was interrupted after the collision. The stopping distance was estimated with time data from the drive recorder. We predict that the brake assist would be effective in preventing secondary collisions in 21% of cases.

## NOTATION

$e$	coefficient of restitution
$V$	speed
$C$	constant
$m$	mass
$L$	length
$t$	time
$D$	deceleration

## INTRODUCTION

Ever more powerful driver assistance systems for critical situations are being developed (Figure 1). A critical driving situation, such as an imminent collision, can be detected at an early stage using assistance systems that include surround sensors. The driver is initially given staged warnings and then, if necessary, is aided by automatic emergency braking and collision avoidance assistance. Furthermore, active safety systems such as electronic stability control (ESC) can stabilize the vehicle during a critical driving maneuver. Passive safety systems, such as airbags, protect the driver should a crash occur. Automatic collision notification systems establish a voice link between the driver and emergency response personnel after an accident.

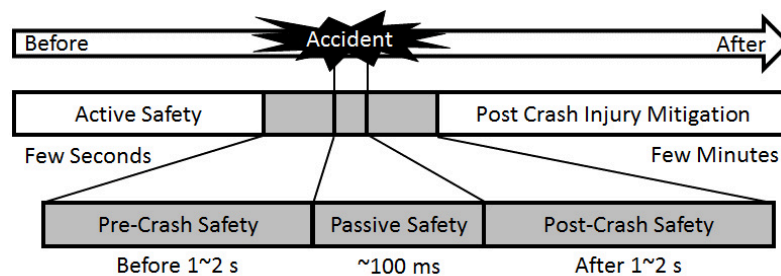


Figure 1. Time line of the development of vehicle safety systems

Post-crash safety systems are one of the promising technologies for minimizing damage in traffic accidents. For example, Hino motor equips their large trucks and buses with post-crash braking systems, which prevent collisions with the vehicle ahead after an initial rear-end collision [1].

Post-crash braking systems are developed for normal passenger cars by auto manufacturers in Europe [2-4]. The system automatically brakes the vehicle after impact when the vehicle is driving at high speed. Thus the system reduces the risk of and the severity of secondary collisions, even if the driver is no longer operating the brake pedal. The extended time span between the initial and secondary collisions provides the driver with more opportunities to intervene. Some post-crash braking systems also have cooperative control with ESC. Consider, for example, the serious situation in which a car is skidding immediately after collision. The ESC activated after the collision helps the driver stabilize the vehicle attitude.

Some post-crash braking systems, however, are designed to stop for traffic signals in rear-end collisions [5]. For example, consider the scenario in which two consecutive vehicles (Vehicle 2 and Vehicle 3 in Figure 2(A)) are stopping at a red traffic signal. A third vehicle (Vehicle 1 in Figure 2(A)) collides with vehicle 2, as shown Figure 2(A). The impact causes vehicle 2 to move towards vehicle 3 (Figure 2(B)). If a post-crash braking system automatically locks the tires during the rear impact, it will reduce the stopping distance. Thus, vehicle 2 prevents a secondary collision with vehicle 3.

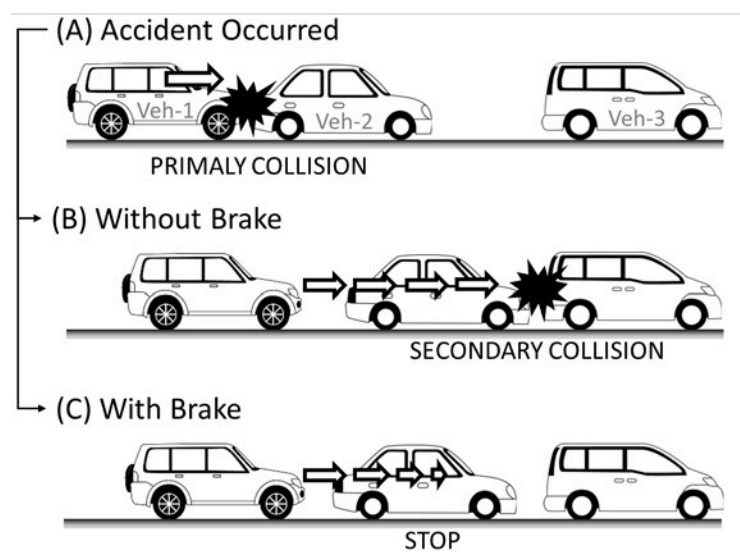


Figure 2. Schematic drawing of rear-end collision with post-crash braking system

## OBJECTIVE

In this paper we evaluated the effectiveness of post-crash braking systems in rear-end collisions. First, we investigated the nature of traffic accidents in Japan and determined from the drive recorder database how many drivers lost brake control after a collision. Next, we estimated by how much the post-crash braking system reduced the stopping distance after collision. Finally, we predicted in how many of these cases that the post-crash braking system prevented a secondary collision.

## METHOD

### Static analysis of rear-end collisions in Japan

In Japan, the traffic static database of fatal and injury accidents is corrected by the National Police Agency. As shown Figure 3, the total number of accidents per year between 2007 and 2012 ranged from 665,138 to 832,454. Of the rear-end collisions, there were 201,891–227,788 cases per year in which the struck vehicle was stopping/braking and 21,755–33,180 cases per year in which the struck vehicle was moving. In this paper, we study a total of 941,591 rear-end collision accidents that occurred between 2007 and 2012.

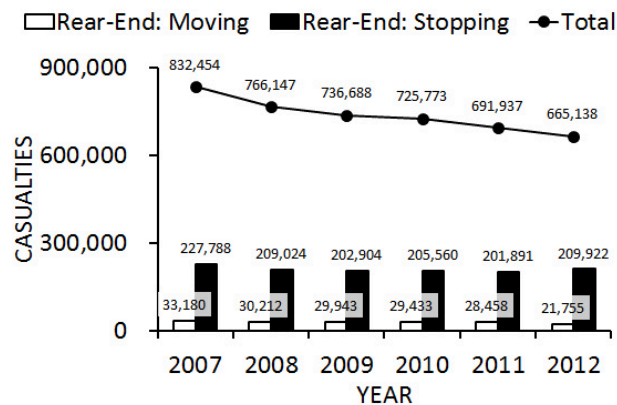


Figure 3. Casualties by traffic accident, including rear-end collisions

### Drive recorder database

We obtained the drive recorder data from the near-crash database of the Japan Association of Automotive Engineers (JSAE) and the Tokyo University of Agriculture and Engineering (TUAE). In January 2013, there were 58,858 cases recorded. Of these there were 319 accidents, 63 of which were rear-end collisions. We analyzed the data from 39 cases in which the struck vehicle was braking at the time of collision. All vehicles with a drive recorder were taxis.

### Physical tests of rear-end collisions

Physical crash tests were performed as shown Figure 4. The speed at collision was measured with a high-speed camera; the test conditions are summarized in Table 1. The striking vehicle and struck vehicle were reused in tests 3–9.



Figure 4. Physical test of rear-end collision

Table 1. Test conditions of the physical vehicle crash tests performed

Test number	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9
Striking vehicle	Corolla A	Corolla B	Noah A	Noah A	Noah A	Noah A	Noah A	Noah A	Noah A
Speed at collision [m/s]	6.95	3.80	6.94	6.02	3.89	4.05	9.94	12.5	5.73
Struck vehicle	Progres A	Progres B	Estima A	Estima A	Estima A	Estima A	Estima A	Estima A	Estima A
Speed at collision [m/s]	0	0	0	0	0	0	0	0	0

## RESULTS AND DISCUSSION

### Static analysis of rear-end collisions

Figure 5 shows the rate of single (two vehicles) and multiple (three or more vehicles) collisions under the following conditions:

- rear-end collision;
- struck vehicle was stopping;
- striking vehicle was passenger car or truck;
- struck vehicle was passenger car or truck;
- damaged part of striking vehicle was the front;
- damaged part of struck vehicle was the rear.

The total number of accidents that occurred in the above conditions was 941,591 over 6 years (2007–2012). Multiple collisions occurred in 13% of rear-end collisions. The static data include accidents in which the struck vehicle hit a motorbike, bicycle, pedestrian or road side objects in a secondary collision.

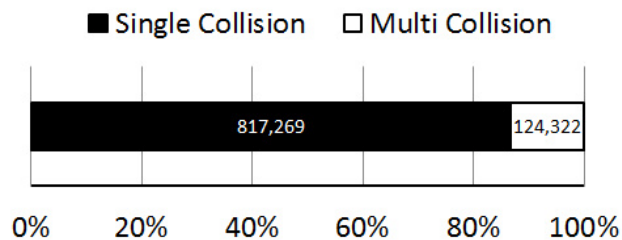


Figure 5. Incidence rate of multiple collisions in rear-end collisions

Table 2 shows the rate of multiple collisions for the situation in which a third vehicle was damaged at the rear, categorized by size of striking–struck vehicle. In each cell in Table 2, the lower value is the total number of rear-end collisions, the upper value is the number of rear-end collisions involving three vehicles, and the rightmost value is the rate of multiple collision accidents. The size category having less than 200 rear-end collisions is disregarded in the following discussion.

A lightweight struck vehicle is at significant risk of multiple collisions if the striking vehicle is a normal/small car because it will experience a considerable change in velocity after collision.

Table 2. Number of rear-end collision accidents

		Striking Vehicle							
		Large Passenger*	Medium Passenger**	Normal Passenger***	Small Passenger	Large Truck*	Medium Truck**	Normal Truck***	Small Truck
Struck Vehicle	Large Passenger*	0 39	0 4	2 507	0 202	3 47	2 60	0 116	0 55
	Medium Passenger**	1 6	19 595	9 338	5 282	2 17	7 172	6 90	1 128
	Normal Passenger***	40 778	42 509	16604 278287	4701 116580	780 7769	1522 12855	2935 42764	1338 34863
	Small Passenger	12 248	29 431	9848 124910	4306 69917	301 3146	597 4746	1476 16980	1180 19111
	Large Truck*	5 21	0 4	5 1006	0 427	146 1088	18 656	5 468	0 211
	Medium Truck**	3 32	2 72	51 3564	6 1263	186 821	200 1482	52 1255	5 628
	Normal Truck***	9 109	6 74	1597 27687	410 10409	255 1494	425 2510	761 7700	177 4411
	Small Truck	8 111	8 155	2936 35525	1135 17003	125 1036	285 2049	678 6817	454 6350

The masked column comprises less than 200 cases.

\* Curb vehicle weight of large passenger/truck is more than 11,000 kg.

\*\* Curb vehicle weight of medium passenger/truck is no more than 11,000 kg.

\*\*\* Curb vehicle weight of normal passenger/truck is no more than 5,000 kg.

The drive recorder database analyzed in the next section was derived from accident data of normal passenger cars. Therefore, the data of normal passenger car were also analyzed in this sentence. Figure 6 shows the speed distribution of normal passenger cars at striking impact. However, 'speed' in the Japanese traffic static database means the speed at which the driver recognized a collision or a risk of collision. The data are categorized into single/multiple collision and struck vehicle type. In single collision accidents, 40% of cases occurred at no more than 10 km/h. In contrast, the same percentage of multiple collision accidents occurred at up to 30 km/h. Thus, multiple collisions tend to occur at higher striking speeds.

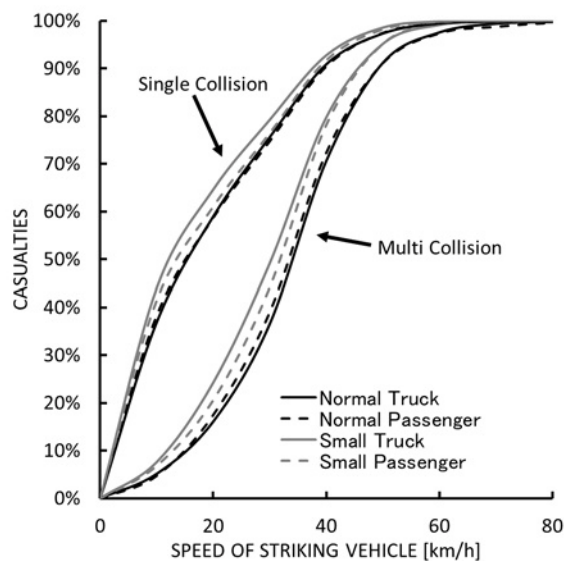


Figure 6. Speed of normal passenger car at striking

## Rear-end collision accident data in drive recorder database

Accidents in which the driver was braking before the rear-end collision occurred are the subject of analysis of the drive recorder database. There were 39 records of rear-end collisions in the drive recorder database that were collected by JSAE/TUAE. In 24 of these cases the striking vehicle had the drive recorder, and in the remaining 15 cases the struck vehicle had the drive recorder. The speed meter and brake pedal switch status were analyzed in the drive recorder data of the struck vehicle. Figure 7 shows the braking release period (vertical line) of the struck vehicle after rear-end collision. In some cases, the brake was switched on and off repeatedly within a short time period. In this situation, it was thought that the driver's foot was shaking on the brake pedal during the accident. In these cases, the total time of repeated switching on/off was defined as the release period. The cases in Figure 7 in which the vehicle speed was 0 km/h correspond to the vehicle stopping at a traffic signal or waiting to turn at an intersection. The case in which the vehicle speed is over 0 km/h was an accident during lane changing. Twelve of the 15 drivers in struck cars with drive recorders released the brake at collision.

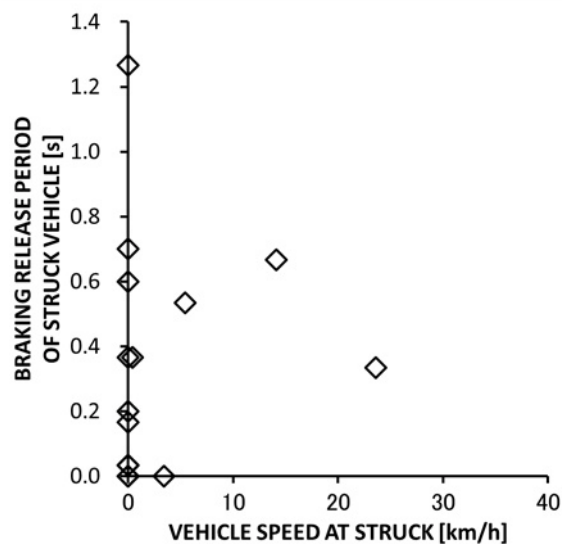


Figure 7. Braking release period of struck vehicle

We analyzed the speed meter data and video images taken by the front camera of struck vehicles with drive recorders. Figure 8 shows the extinguished period of the brake lamp of the struck vehicle (vertical line) after a rear-end collision, estimated from video images taken by the front camera of the striking vehicle. In some cases, the data repeated 'lamp on'/'lamp off' during a short time period, which likely indicates that the driver's foot was shaking on the brake pedal during the accident. In that case, the total time in repeated 'lamp on'/'lamp off' during a short time period is defined as the extinguished period, as in Figure 8.

In 13 of the 24 cases, the struck vehicle extinguished its brake lamp upon collision. There did not appear to be any relationship between the speed of the striking vehicle and the extinguished period of the struck vehicle.

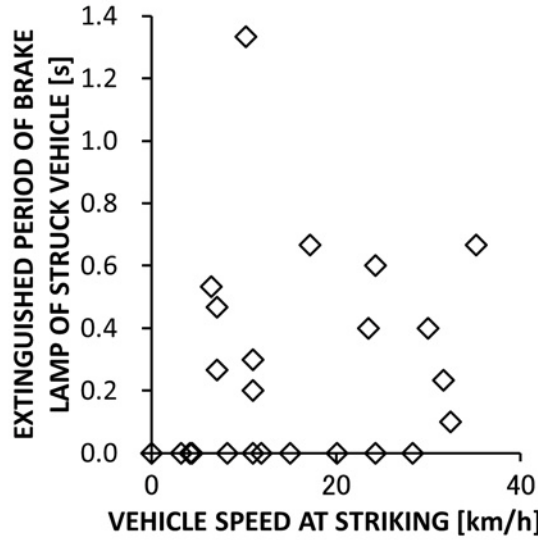


Figure 8. Brake lamp extinguished period of struck vehicle

In 64% (25/39 cases) of all rear-end collisions, the driver's braking of the struck vehicle was interrupted.

### Reduction of stopping distance with post-crash braking system

#### *Speed of struck vehicle after rear-end collision*

The speed of the struck vehicle after a rear-end collision is needed to calculate the stopping distance. However, the drive recorder is not accurate enough to resolve this speed because the sampling rate of the speed is 30 Hz and the collision impact lasts only approximately 100 ms. Moreover, the speed is recorded by the rotation of the wheels, which is not accurate enough to measure the speed after collision. The struck vehicle speed is estimated from the initial speed of the striking vehicle by conservation of momentum and restitution,

$$m_1 V_{10} + m_2 V_{20} = m_1 V_1 + m_2 V_2, \quad [1]$$

$$e = -\frac{V_2 - V_1}{V_{20} - V_{10}}, \quad [2]$$

where  $V_{10}$ ,  $V_1$  and  $m_1$  are the initial speed (m/s), post-collision speed (m/s) and weight (kg) of the striking vehicle, respectively,  $V_{20}$ ,  $V_2$  and  $m_2$  are the analogous quantities of the struck vehicle, and  $e$  is the coefficient of restitution.  $V_{20}$  in all cases was 0 m/s, because all struck vehicles were initially at rest.  $V_2$  is given by

$$V_2 = \frac{m_1}{m_1 + m_2} (1 + e) V_{10} \quad [3]$$

This equation shows that  $V_2$  depends on the weight of the struck vehicle. A secondary collision occurs more easily for a lighter struck vehicle, as evidenced by the static results in Table 2. The striking speed in Figure 8 was used as the value of  $V_{10}$ .

#### *Coefficient of restitution in rear-end collision*

The relationship between the collision speed and the vehicle speed after collision depends on the coefficient of restitution. Assuming that the energy in elastic restoration does not depend on the collision speed, then the coefficient of restitution is inversely proportional to the collision speed [6-7]. Therefore, the coefficient of restitution in rear-end collisions is defined as

$$e = \frac{C}{V_{10}-V_{20}}, \quad [4]$$

where C is a constant that is derived from results of physical tests (Table 1). The test results are shown in Figure 9.

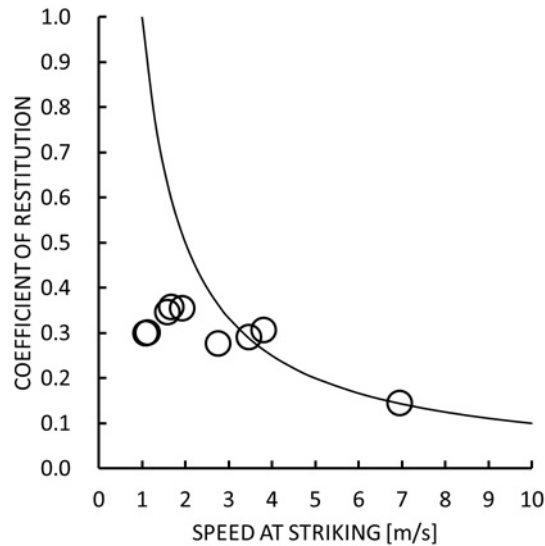


Figure 9. Results of rear-end collision tests

The constant C is assigned the value 1.00 (solid curve in Figure 9). The relationship between the coefficient of restitution and the collision speed is given by

$$e = \frac{1.00}{V_{10}-V_{20}}. \quad [5]$$

### Estimation of stopping distance

Figure 10(A) shows the modelled braking curve of the struck vehicle in an accident. The braking is interrupted at collision, then, the driver resumes braking, and the struck vehicle comes to rest. The stopping distance  $L_2$  of struck vehicle is calculated as follows:

$$L_2 = V_2 t_2 + \frac{V_2^2}{2D_2}, \quad [6]$$

where  $t_2$  and  $D_2$  are the time period without braking (s) and the deceleration ( $m/s^2$ ) of the struck vehicle, respectively. If the struck vehicle has a post-crash braking system, the struck vehicle automatically stops, as shown in Figure 10(B); i.e.,  $t_2 = 0$  s.

Let the striking vehicle weight be 1400 kg, that of a typical taxi in Japan [8], and the struck vehicle weight be 800 kg for a small car, 1400 kg for a normal passenger car, and 3000 kg for a normal truck. The deceleration in braking is assumed to be 0.8 G ( $7.84 m/s^2$ ).



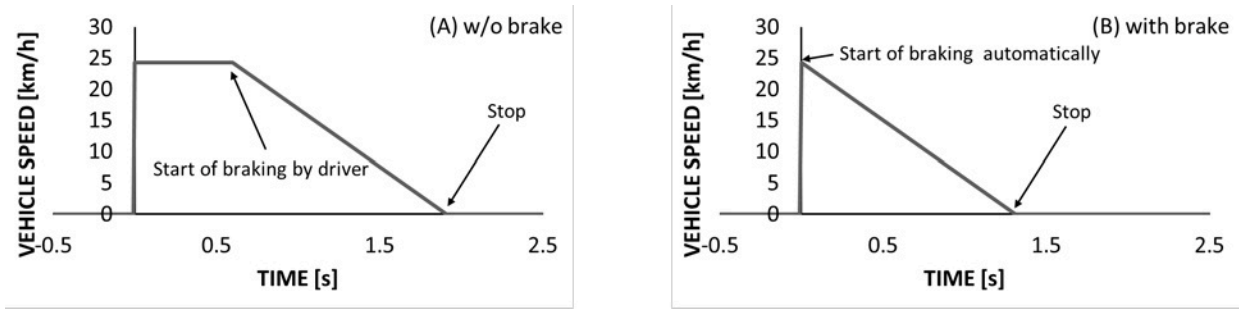


Figure 10. Brake timing after collision

Figure 11 shows the predicted stopping distance of a struck vehicle after collision. The positions of the diamond markers were determined with the assumption that  $t_2 = 0$  s. The square markers correspond to the  $t_2$  values from the database. The effectiveness of the post-crash braking system is indicated by the amount that the square marker values exceed the values of the diamond markers. In the case where the diamond and square markers coincide, the driver brakes continuously during the accident. The post-crash braking system was not effective in the case.

Let the struck vehicle follow a (preceding) vehicle, as shown Figure 2. Vehicle 1 approaches these two vehicles, which are stopping. Let the distance between vehicle 2 and vehicle 3 be 2.5 m [9]. If vehicle 2 moves forward more than 2.5 m, a secondary collision occurs between vehicle 2 and vehicle 3. If the stopping distance were reduced to less than 2.5 m by the post-crash braking system, then the secondary collision would be prevented. In Figure 11, the estimated stopping distance is reduced by less than 2.5 m in five cases (21 %). On the other hand, in 18 cases, the driver of the struck vehicle continues braking or resumes braking quickly after the interruption of the vehicle impact. Therefore, the driver's braking is interrupted at collision for a long enough time to reach a preceding vehicle in 21% of cases. In one case of a normal passenger car colliding with a small passenger car, shown in Figure 11, the stopping distance with the post-crash braking system was more than 2.5 m. The struck vehicle moved at high speed after the collision because it was lightweight.

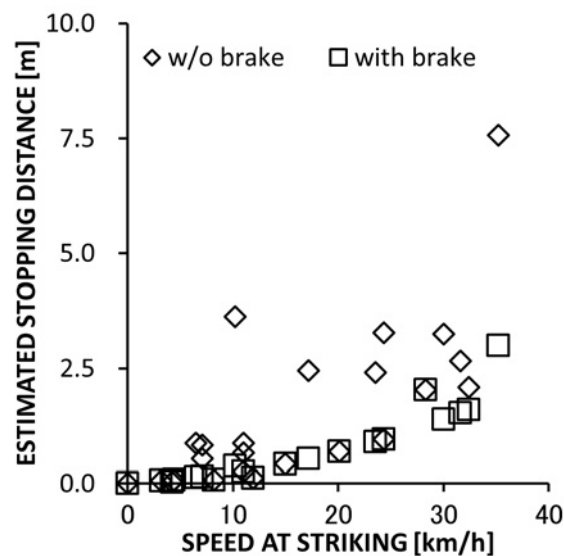


Figure 11. Estimated stopping distance after collision

## Estimation of effectiveness with static analysis

The effectiveness of a post-crash braking system was estimated by static analysis of accident data from Japan over a 6-year period (2007-2012). High speed and heavy striking vehicles increase the risk of secondary collisions. There exists a critical striking speed for each vehicle weight at which the struck vehicle can come to rest within 2.5 m, which is listed in the first row of Table 3. The striking vehicle weight is assumed to be that of a normal passenger car (1400 kg). The second row in Table 3 shows number rate at critical speed in Figure 6. The third row in Table 3 shows the effectiveness of post-crash braking system in Figure 11. The fourth row in Table 3 shows the incidence rate of multiple rear-end collisions that occur in Japan under the aforementioned critical speed (Figure 6). The fifth row in Table 3 shows the number of accidents in which the striking speed was less than the critical speed, as shown in the first row in Table 3. The cases in which the post-crash braking system (the sixth row of Table 3) is predicted to be effective for the incidence rate (the fourth row of Table 3) and for the number of accidents (the fifth row of Table 3). The total number of effective cases was estimated at 4,006 over the 6 years (the seventh row of Table 3). The annual average over the 6 years was 668. This demonstrates the effectiveness of the post-crash braking system for a vehicle struck by a normal passenger car. Although this system cannot prevent secondary collisions, it does reduce their severity.

Table 3. Effectiveness of post-crash braking system for normal passenger cars

	STRUCK VEHICLE			
	Normal Passenger 1400kg	Small Passenger 800kg	Normal Truck 3000kg	Small Truck 800kg
Critical Speed to Stop by 2.5 m (km/h)	40	30	70	30
Number Rate at Critical Speed in Fig.6 (%)	72	44	99	49
Effectiveness of Post-Crash Braking System at Fig.11 (%)	21			
Incidence Rate under Critical Speed (%)	15	9	21	10
Number of Accidents at Table 2	16604	9848	1597	2936
Effective Case of Post Crash-Braking System	2491	886	335	294
Total Number of Effective Case	4006			

## CONCLUSION

Twenty-eight percent of traffic accidents in Japan are rear-end collisions, and 13% of these are multiple collisions. A post-crash braking system helps the driver stop the vehicle in a shorter distance after a rear-end collision to prevent a secondary collision. In this study, the effectiveness of a post-crash braking system was examined using a drive recorder database. In 64% of rear-end collisions, the driver's braking was interrupted after the collision. It is estimated that the brake assistance of the post-crash system would be effective in 21% of cases to prevent a secondary collision. Nonetheless, it is not possible to avoid a secondary collision in accidents at sufficiently high speeds. In Japan, considering the velocity distribution of striking vehicles in rear-end collisions, it is predicted that the brake assistance provided by the post-crash system would prevent secondary collisions in 668 accidents per year for normal passenger cars.

## ACKNOWLEDGMENT

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