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Experimental study on car collisions with bicycles equipped with child seats

Takaaki Terashima [a,b,*], Kenshiro Kato [a], Ryo Oga [a], Nobuaki Takubo [a], Koji Mizuno [c]

[a] National Research Institute of Police Science, 6-3-1, Kashiwanoha, Kashiwa-shi, Chiba 277-0882, Japan
[b] Nagoya University, Graduate School of Engineering, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan
[c] Nagoya University, Department of Mechanical Science and Engineering, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan

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ABSTRACT

In Japan, traffic accidents involving bicycles have become a serious problem as a result of the increase in the use of bicycles due to the rising concerns of environmental and health problems. In recent years, bicycles equipped with child seats have become a popular means of transportation for preschool children in urban areas in Japan. Under such adverse circumstances, it is necessary to conduct more studies and evaluations to prevent traffic accidents and the resulting injuries involving bicycles with children. For accident prevention and damage mitigation, this study mainly aims to understand the kinematic behavior and injury risk of children in collisions involving bicycles equipped with child seats through experiments. First, fall tests were conducted to evaluate the effect of the integrated head restraints (also commonly known as headrests) of child seats. It was confirmed that head restraints can reduce the impact of head collisions with the road surface. Second, side collision tests were conducted between a car and a bicycle equipped with a child seat, and the effects of the seat belt and head restraint of the child seat were investigated. It was shown that the kinematic behavior of the child dummy significantly was changed depending on wearing the seat belt. In the condition that the seat belt was not fastened, the child dummy was ejected out of the child seat while rotating toward the hood after the impact with the front of the car. In contrast, when the seat belt was fastened, the child dummy was restrained in the child seat and moved together with the bicycle from the start of the collision until the complete stop. Thus, it was found that using child seats with head restraints and using seat belts can reduce the risk of injury to children during an impact with the road surface, because the child dummy in the tests impacted the road surface only after the bicycle already had contact with the road surface.

1. Introduction

The proportion of children in Japan's population is declining year by year (Cabinet Office of Japan, 2019a), and the declining birthrate has become a social problem. Therefore, it is vital to realize a society in which parents can raise their children with peace of mind. Unexpected accidents are a major cause of child deaths in Japan. In particular, traffic accidents account for a high proportion of accidents involving children (Statistics Bureau of Japan, 2019). Therefore, traffic safety for children is being promoted by the government as one of the measures for increasing the child population despite the declining birthrate (Cabinet Office of Japan, 2019b).

In Japan, traffic accidents involving bicycles have become a serious problem with the increase in the use of bicycles due to the rising concerns of environmental and health problems. In addition, the government is promoting the improvement of bicycle use environments as a safety measure (Ministry of Land, Infrastructure, Transport and Tourism of Japan., National Police Agency of Japan, 2016). In particular, bicycles equipped with child seats have become popular in urban areas in Japan because they can be easily used as transportation means for preschool children (Japan Bicycle Promotion Institute, 2006). Under such circumstances, it is necessary to conduct more studies and evaluations to prevent traffic accidents and mitigate injuries involving bicycles with children.

There are some types of bicycles that carry children. One of them is equipped with one or two child seats, another one tows a trailer designed for carrying children, and yet another one is equipped with a large cargo area like a box for children. Under Japanese law, in principle, bicycles must run on the roadway. Therefore, bicycles towing trailers and equipped with cargo areas for children are not allowed to run on sidewalks. However, bicycles equipped with child seats are allowed to run on sidewalks only in exceptional cases. In addition, there

* Corresponding author at: Department of Traffic Science, National Research Institute of Police Science, 6-3-1, Kashiwanoha, Kashiwa-shi, Chiba 277-0882, Japan.
E-mail address: terashima@nrips.go.jp (T. Terashima).

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are many places in which roads are narrow, especially in urban areas, which makes it dangerous to ride a bicycle carrying children on the roadway. Many bicyclists carrying children tend to run on sidewalks (Yano et al., 2016; Ueda et al., 2015). Thus, under such traffic conditions in Japan, bicycles equipped with child seats are the most popular, and other styles are less available (Japan Bicycle Promotion Institute, 2006). Almost all child seats are equipped with seat belts to prevent children from falling out of the seat, and some seats are equipped with integrated head restraints to protect the child's head during head impact when he/she falls.

In the United States and Australia, it has been reported that the head or face of children on bicycles was the most common site of an injury by an accident (Oxley et al., 2016; Powell and Tanz, 2000). These include many injuries associated with bicycles equipped with child seats involved in falls and other non-traffic incidents. Unfortunately, there is little data on such traffic accidents. In Japan, no traffic accident analyses have been conducted on using bicycles that carry children; and due to having no available information from such studies, the basis of taking appropriate measures against traffic accidents has been insufficient. In our previous study, we analyzed the traffic accident situation of bicycles carrying children using the Japanese traffic accident database (Terashima et al., 2015). This study showed that bicycles carrying children often had accidents with normal-size cars and mini cars (K-cars) and showed that many of those accidents were crossing collisions at intersections. In most of the accidents, the speed of the cars was 30 km/h or less, and many children that were carried on bicycles were injured at their heads and faces after impact with the road surface. Zander et al. (2013) performed collision tests of bicycles equipped with child seats. In their tests, a sedan collided with the bicycle. They examined the impact condition on the child dummy's head in the collision against the car with measuring the wrap around distance (WAD). In addition, Ptak et al. (2019) investigated the kinematic behavior of the cyclists and children in a collision with a car through numerical simulations. However, the phenomenon until the cyclists and children fall on the road surface after the impact with the car has not been included. In order to obtain more knowledge on the damage mitigation during accidents, we conducted rear-end collision tests with a bicycle equipped with a child seat without a head restraint and investigated the kinematic behavior of the cyclists and children until the complete stop on the road (Terashima et al., 2018). The bicycle occupant kinematic behavior after the rear-end collision and the potential of the child seat's seat belt to reduce injury were determined.

According to a 2006 report (Japan Bicycle Promotion Institute, 2006), the rate of using the seat belts available on child seats was approximately 54%, and most of the child seats did not have head restraints. It has been reported that the seat belts and back seat height affect the impact on the child dummy's head in a fall of a bicycle equipped with a child seat (Miyamoto and Inoue, 2010). However, the high-back child seat used in the literature had small side walls, which is different from the child seat that has the high back and the large side wings (that we call the head restraint) commonly used in Japan.

The protection of child seats with large side wings during side collisions that frequently occur in Japan has not been understood yet. Hence, the purpose of this study is to understand the kinematic behavior of children in the child seat of bicycle subjected to side collisions as well as to study the injury risks resulting impact with a car and the road surface. First, we performed tests of a child dummy in a child seat falling toward the ground to evaluate the performance of the head restraint with the large side wings. Second, we performed car-to-cyclist side collision tests which are most common in accidents. Then, we evaluated the use of seat belts and head restraints based on the kinematic behavior of child dummies in order to evaluate their protective abilities.

2. Method

2.1. Fall tests

The fall tests were conducted to evaluate the effect of head restraints with child seats since it was revealed in the previous study that children on bicycles are usually injured at their heads after a collision with the road surface (Terashima et al., 2015). The tests were performed using the equipment shown in Fig. 1. The equipment has a child seat placed on a table (H = 725 mm) that is about the same height as that of the rear carrier of a 26-inch bicycle. This setup is designed so that the seat rolls backward and makes an impact with the road surface. In the tests, a child dummy (Hybrid-III 3YO) was seated on the child seat, and the seat belt was fastened. The tests were conducted 5 times each with and then without the head restraint of the child seat (Fig. 2).

The state of the fall was captured by high-speed video cameras (500 fps). Also, the speed of the dummy's head and the child seat were analyzed using the images of the cameras, assuming that the influence of the motion in the screen depth direction was small and that the motion was two-dimensional with respect to the screen. An accelerometer was attached to the head of the child dummy, and the triaxial acceleration during a test was measured at 20 kHz. In the analysis, the acceleration data was filtered by the channel frequency class (CFC) 1000 specification (SAE J211). The Head Injury Criterion (HIC) was calculated from the head resultant acceleration to evaluate head injury risk:

$$HIC = \left\{ \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t)dt \right]^{2.5} (t_2 - t_1) \right\}_{max}$$

t_1, t_2: two arbitrary times during the acceleration pules.
a(t): the head resultant acceleration (g).

2.2. Car-to-cyclist collision tests

We conducted car-to-bicycle collision tests in order to understand the characteristics of the accidents in more detail. In the tests, the conditions of the seat belt and head restraint of the child seat were changed, and the effects of each condition were evaluated. Fig. 3 shows the configuration of the car-to-bicycle collision tests. When simulating side collisions, the front of the car hit the left side of the bicycle, and the location of the impact was where the bicycle saddle was within ±0.2 m from the center of the car. Fig. 4 and Table 1 show the used car, bicycles, and child seats in the tests. An adult female dummy (Hybrid-III AF05) rode on the bicycle with the right foot in the bicycle's aft direction and the left foot in the frontal direction, and a child dummy (Hybrid-III 3YO) sat on the child seat on the rear carrier. The target collision speeds of the bicycle were set to 4.2 m/s (15 km/h) which was a typical traveling speed (Mori et al., 2015), and 0 m/s. The test car was a sedan (Toyota Premio, model: TA-ATZ240), and its gross weight was 1226 kg. As a result of the traffic

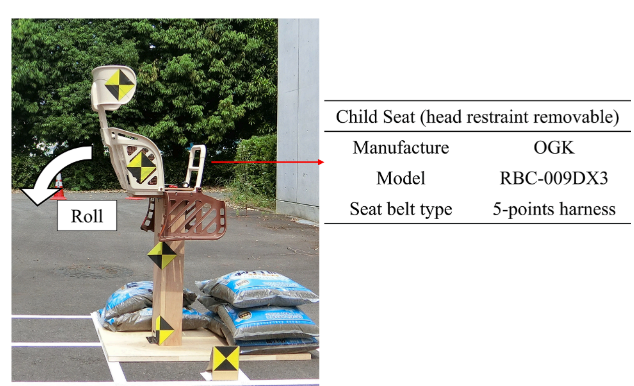


Fig. 1. Equipment of the fall tests.

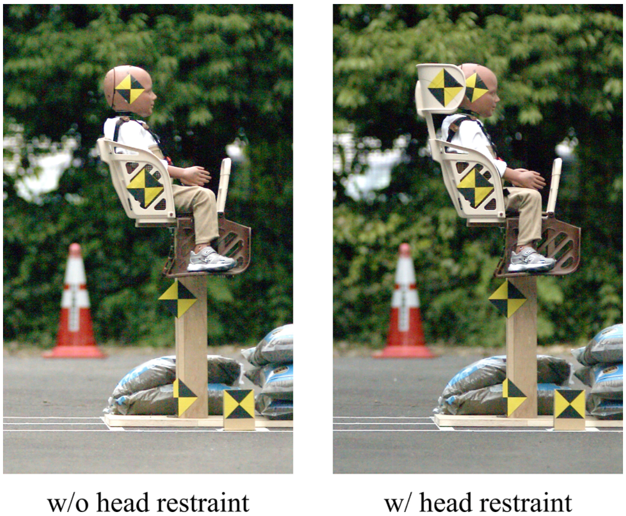


Fig. 2. Fall test conditions.

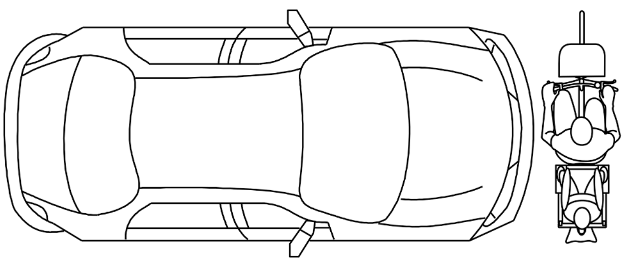


Fig. 3. Configuration of car-bicycle collision tests.

Fig. 4. Test car.

accident analysis (Terashima et al., 2015) in which the speed of the car in 98% of the accidents was 30 km/h or less, the target collision speed of the car was set to 8.3 m/s (30 km/h), and braking was immediately performed after the collisions. Table 2 shows the target collision speed of the vehicles and the conditions of the seat belt and the head restraint of the child seat in each test. In addition, helmets were not used in the tests in order to evaluate the effects of the seat belt and the head restraint of the child seat.

An external optical speed sensor was used to obtain the collision speed of the cars and the bicycles, and the dummy's kinematic behavior was captured by high-speed video cameras (500 or 1000 fps). The velocity of the dummy's head was calculated using the recorded images from the high-speed video camera. It was assumed that the influence of the motion in the screen depth direction was small and that the motion was two-dimensional with respect to the screen. The HIC was calculated from the calculated head resultant acceleration to evaluate head injury risk.

3. Results

3.1. Fall tests

Fig. 5 shows frames of the high-speed video images of the dummies during the fall tests. The child dummy rotated toward the road surface while sitting on the child seat, and in the condition without a head restraint, the dummy's head directly hit the road surface. Meanwhile, in the condition with the head restraint, the dummy's head hit the road surface via the head restraint. There was no significant deformation of the head restraint after the collision. Table 3 shows the maximum values of the target mark speed of the dummy's head, the head restraint, and the child seat. It also shows the maximum resultant acceleration of the dummy's head and HIC_{15}. The speed values of the target marks of the dummy's head, head restraints, and child seats were highest immediately before the collisions with the road surface.

We compared differences in the maximum speed of the head or head restraint, the maximum speed of the child seat, the maximum head resultant acceleration, and HIC_{15} between the condition with or without the head restraint using Welch's *t*-test. A significant difference was found for the maximum speed of the head or head restraint, the maximum head resultant acceleration, and HIC_{15}. The average maximum speed of the head was higher than that of the head restraint ($t(4) = 6.79$, $p = .002$). The average of the maximum head resultant acceleration in the condition without a head restraint was much higher than that in the condition with a head restraint ($t(8) = 39.9$, $p < .001$). In addition, The average of HIC_{15} was significantly different ($t(6) = 37.8$, $p < .001$). There was no significant difference in the average of the maximum speed of the child seat.

In FMVSS 208, the value of HIC_{15} for the safe protection of 3-year-old car occupants in the event of frontal collisions is 570. The HIC_{15} limit value of 570 has a 31% probability of skull fracture (MAIS $\geq$ 2) (Eppinger et al., 1999). In these tests, it should be noted that the impact in the fall to the road surface was not a frontal impact, but the value of HIC_{15} in the condition without a head restraint exceeded the acceptance level.

3.2. Car-to-cyclist collision tests

3.2.1. Kinematic behavior of the dummies and bicycles

In all the tests, the collisions were performed according to the specified test conditions. Fig. 6 shows frames of the high-speed video images of the dummies during the collision tests. In all of the tests, after the impact by the car bumper (0 ms), the adult and child dummies rotated toward the hood, and the bicycle was lifted by the legs of the adult dummy. Also, the bicycle was pushed away by the car in its direction of travel, dropped onto the road surface, slid, and then came to a stop.

In Test 1, the left leg of the adult dummy was impacted by the bumper of the car, and then the left side of the pelvis impacted the front part of the hood. As the lower half of the body was pushed in the car's direction of travel, the adult dummy rotated toward the hood while sliding over it, and then its left hand, left shoulder, and left side of the head (200 ms) made impacts against the hood. After that, as the car braked, the adult dummy fell from the side of the car's left fender. Then, after the dummy collided with the road surface in the sequence of the left foot, left arm, left shoulder, and left torso impacts (1055 ms), the dummy slid on the road surface and then stopped in a prone position.

As for the child dummy, its first impact was its left leg contacting the radiator grille of the car. Then, the lower half of the body and the bicycle were pushed by the car, resulting in the child dummy being ejected out

Table 1
Test bicycles.

Test No.	1	2	3	4
Bicycle				
Manufacture	BRIDGESTONE	BRIDGESTONE	ASAHI	BRIDGESTONE
Model	YUUVI II	YUUVI II	Fromage Lis Blanc	YUUVI II
Tire size [inch]	26	26	27	26
Weight including child seat [kg]	24.6	26.1	22.6	26.9
Photo				
Child Seat				
Manufacture	OGK	BRIDGESTONE	OGK	BRIDGESTONE
Model	RBC-009S3	RCS-LD4	RBC006N	RCS-LD4
Seat belt type	3-point (Removed)	5-point (Removed)	4-point harness	5-point harness
Photo				

Table 2
Collision test conditions.

Test No.	Speed of car [m/s]	Speed of bicycle [m/s]	Child seat	
			Head restraint	Seat belt
1	8.3	4.2	w/o	w/o
2	8.3	0	w/	w/o
3	8.3	0	w/o	w/
4	8.3	4.2	w/	w/

of the child seat while rotating toward the hood. After its head (145 ms) and left arm impacted the hood, the child dummy was thrown above the hood while rotating in the air. The left foot impacted the front window and the hood; and as the car braked, the child dummy fell from the side of the car's left fender. Then, after the child dummy collided with the road surface in the sequence of the right foot, right back, and head (1154 ms) impacts, it slid on the road surface and stopped with its left side down.

In Test 2, the left leg of the adult dummy was impacted by the bumper of the car, and then the left side of the pelvis impacted the front part of the hood. As the lower half of the body was pushed in the car's direction of travel, the adult dummy rotated toward the hood while sliding over it. Then, its left arm and the back of the head made impacts (143 ms) against the hood, and its head impacted the front window. After that, as the car braked, the adult dummy fell to the front of the car. Then, after the dummy collided with the road surface in the sequence of the left foot, pelvis (1251 ms), right foot, left arm, and head impacts, it slid on the road surface and then stopped with its left side down.

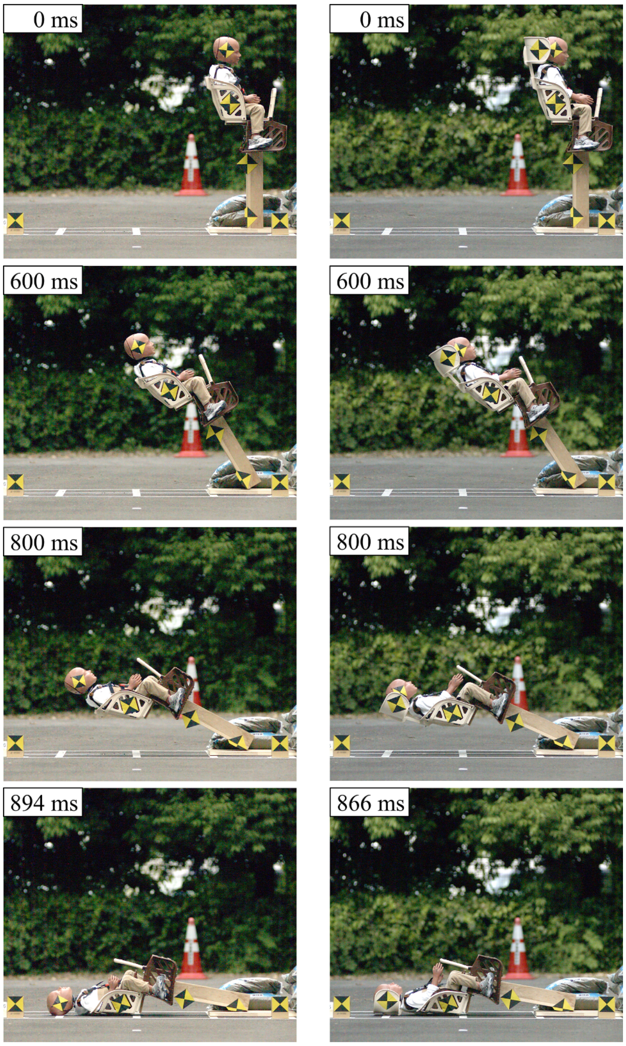
As for the child dummy in Test 2, its left leg was impacted by the car's radiator grille. Then, the lower half of the body and the bicycle were pushed by the car, and the child dummy was ejected out of the child seat while rotating toward the hood. After its left arm and head (107 ms) impacted the hood, it was thrown above the hood. Afterward, it rotated in the air and then turned upside down, where its head impacted the hood again. As the car braked, the child dummy fell to the front of the car, where its left foot, right foot, and pelvis (1063 ms) impacted the road surface, respectively in that sequence. After that, the dummy slid on the road surface while rotating to the left side, had its head impact the road surface, and then stopped the left side down.

In Test 3, the left leg of the adult dummy was impacted by the bumper of the car, and then the left side of the pelvis impacted the front of the hood. As the lower half of the body was pushed in the car's direction of travel, the adult dummy rotated toward the hood, and then its left arm, back of the head (171 ms), and back impacted the hood. After that, as the car braked, the adult dummy fell to the front of the car. Then, after colliding with the road surface in the sequence of the left foot, right foot, and pelvis (1120 ms), the dummy slid on the road surface and finally stopped with its right side down.

As for the child dummy in Test 3, it first was impacted by the car's radiator grille. As the lower half of the dummy's body and the bicycle were pushed by the car and since the dummy's body was restrained by the seat belt, the child dummy seated on the child seat rotated along with the bicycle toward the hood. After the dummy's left arm hit its head, the then head hit the hood (105 ms). Afterward, as the car braked, the child dummy and the bicycle fell to the front of the car on the road surface upside down, where the child dummy impacted the road surface in the sequence of the right hand, head (830 ms), face, and chest. Then, the child dummy slid on the road surface and stopped with the right side down. Because of the seat belt, the child dummy moved together with the bicycle while sitting on the child seat from the start of the collision until the crash event was completed.

In Test 4, the left leg of the adult dummy was impacted by the bumper of the car, and then the left side of the pelvis impacted the front of the hood. As the lower half of the body was pushed in the car's direction of travel, the adult dummy rotated toward the hood while sliding over it. Then, its left hand, left arm, and left head (115 ms) impacted the hood. After that, the adult dummy rotated in the prone direction, and the head impacted the hood again. As the car braked, the dummy fell to the front of the car. Then, after colliding with the road surface in the sequence of the right leg, left knee, right knee, right hand, and pelvis (951 ms), the dummy slid on the road surface and stopped in the prone position.

As for the child dummy in Test 4, it first was impacted by the radiator



w/o head restraint w/ head restraint

Fig. 5. Kinematic behaviors of the dummies in the fall tests.

grille of the car. As the lower half of the dummy's body and the bicycle were pushed by the car and since the body was restrained by the seat belt, the child dummy while sitting on the child seat rotated along with the bicycle toward the hood. The left arm impacted the hood, and then its head impacted the hood via the left arm (84 ms). After that, as the car braked, the child dummy fell to the front of the car together with the bicycle on the road surface with the left side down, where the bicycle stand, rear wheel, front wheel, and handle were in contact with the road. Then, after the left leg of the child dummy touched the ground, the head impacted the road surface via the head restraint (810 ms). The child dummy together with the bicycle slid on the road surface and then stopped with the left side down. Because of the seat belt, the child dummy moved together with the bicycle while sitting on the child seat from the start of the collision until the entire crash event was completed.

In all the tests, no collisions between the two dummies were observed during the entire crash event.

3.2.2. *Head acceleration of the child dummy*

Fig. 7 shows the resultant acceleration of the child dummy's head. In all the tests, there were multiple peaks during the head resultant acceleration.

In Test 1, the peak at about 150 ms was caused by the impact of the head of the child dummy with the hood of the car, and the peak at about 1150 ms was caused by the impact of the head with the road surface.

In Test 2, the peak at about 110 ms was caused by the impact of the head of the child dummy with the hood of the car, and the peak at about 1060 ms was caused by the collision of the pelvis with the road surface. The peak at about 1320 ms was caused by the impact of the head with the road surface.

In Test 3, the peak at about 80 ms was caused by the impact of the left arm of the child dummy with the head when the child dummy rotated toward the hood. The peak at about 100 ms was caused by the impact of the head with the hood of the car, and the peak at about 830 ms was caused by the impact of the head with the road surface.

In Test 4, the peak at about 90 ms was caused by the impact of the head of the child dummy with the hood of the car via the left arm, and the peak after about 810 ms was caused by the impact of the head with the road surface via the head restraint.

In the tests, a large head resultant acceleration occurred during the impact of the left arm with the head when the child dummy rotated toward the hood, during the impact of the head with the hood of the car, and during the impact of the head with the road surface. Table 4 shows the maximum values of the resultant acceleration of the child dummy's head and the HIC_{15} resulting from the impacts with the cars and road surfaces.

In the FMVSS 208, the acceptance level of HIC_{15} of a 3-year-old car occupant in a frontal collision is 570. In this study, it should be noted that while it is the acceleration of the bicycle occupant's head (and not that of a vehicle's occupant), the results of Tests 1 and 3 exceeded the acceptance level of HIC_{15}.

4. Discussion

4.1. *Fall tests*

The maximum speed experienced by the child dummy's head in the condition without the head restraint was slightly higher than that with the head restraint. However, in both conditions, as the maximum value of the child seat speed was about the same, it is likely that the child dummy fell to the road surface at about the same speed. Also, in the condition without the head restraint, the maximum value of the head

Table 3
Results of the fall tests.

Test condition	Fundamental statistics	Max. speed of head or head restraint* [m/s]	Max. speed of child seat [m/s]	Max. head resultant acceleration [m/s^2]	HIC_{15}
w/o head restraint (N = 5)	Mean (95% CI)	4.71 (4.69–4.74)	3.07 (3.02–3.13)	3484 (3342–3626)	1845 (1745–1944)
	SD	0.02	0.05	114	80
	Max	4.74	3.13	3596	1935
	Min	4.68	3.03	3300	1755
w/ head restraint (N = 5)	Mean (95% CI)	4.17 (3.95–4.39)	3.13 (3.10–3.16)	900 (789–1010)	346 (298–393)
	SD	0.18	0.03	89	38
	Max	4.38	3.16	1029	388
	Min	4.01	3.10	781	303

*: Target mark speed of the head in the condition without a head restraint. Target mark speed of the head restraint in the condition with the head restraint.

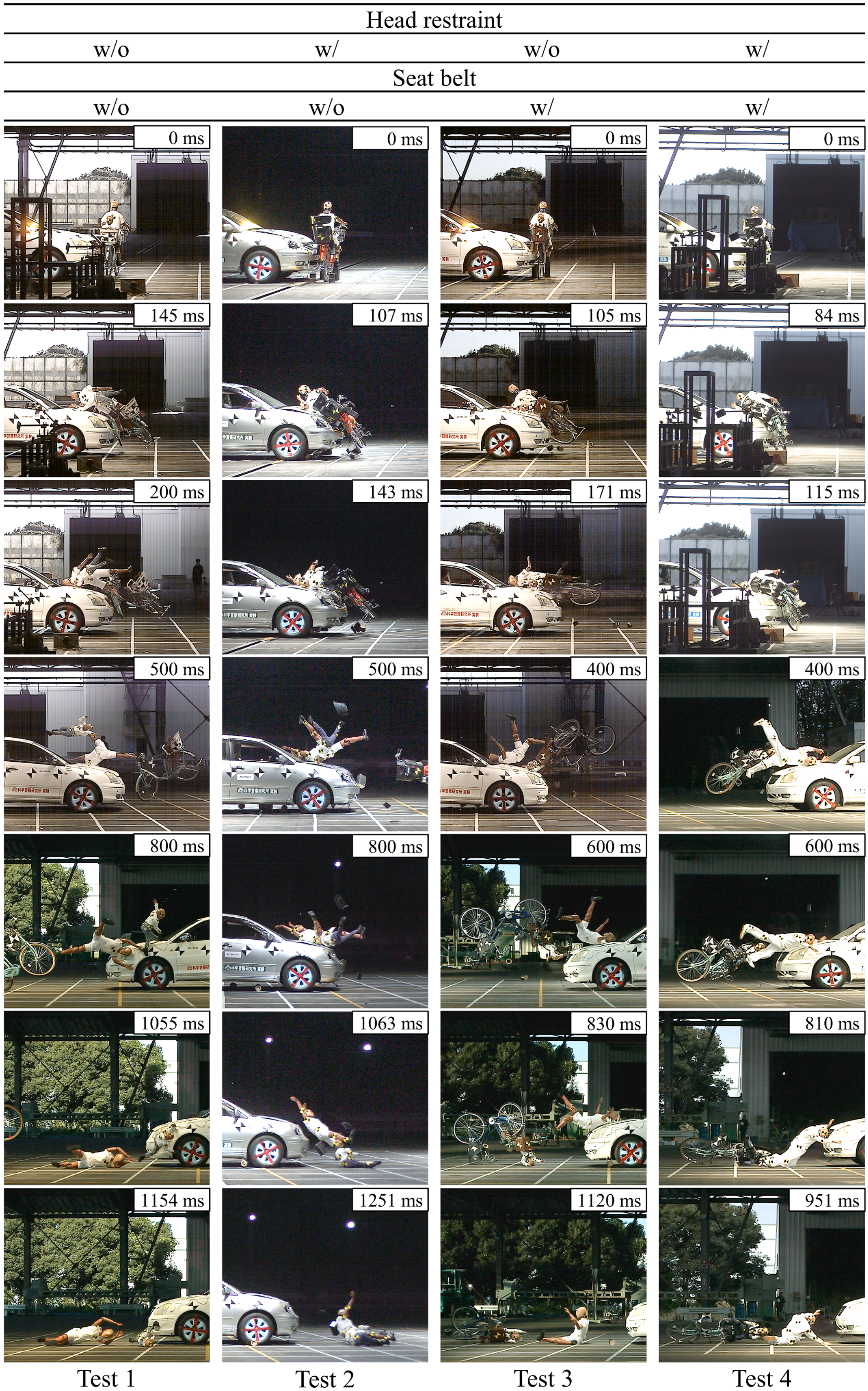


Fig. 6. Kinematic behaviors of the dummies and the bicycles in the collision tests.

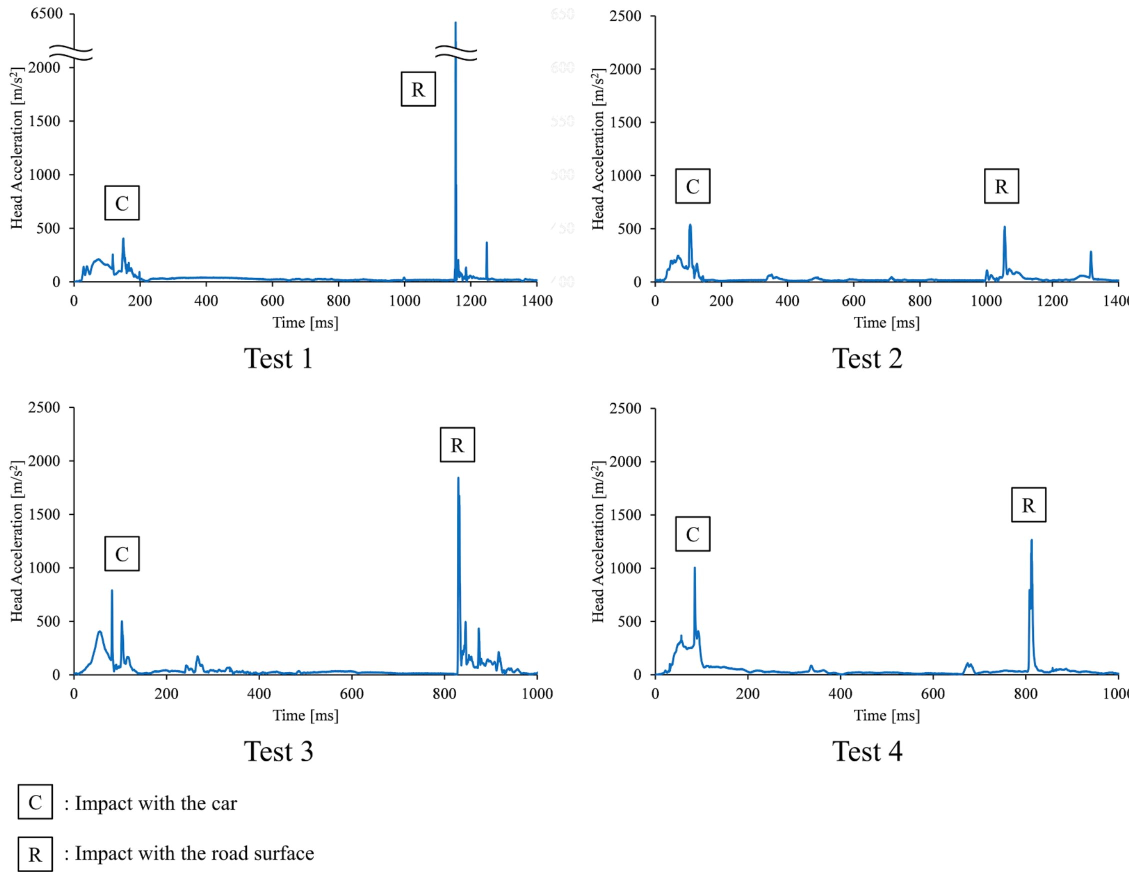


Fig. 7. Child dummy head resultant acceleration in the collision tests.

Table 4
Maximum head resultant acceleration and HIC_{15} of the child dummy in the collision tests.

Test No.	Impact with the car		Impact with the road surface	
	Max. head resultant acceleration [m/s^2]	HIC_{15}	Max. head resultant acceleration [m/s^2]	HIC_{15}
1	405	42	6421	9168
2	539	114	520*	69*
3	789#	131#	1843	1219
4	1006	178	1266	521

*: The impact of the pelvis with the road surface
#: The impact of the left arm with the head.
No mark: The impact of the head with the hood or the road surface.

resultant acceleration was extremely high at 3484 m/s^2, and the resulting HIC_{15} was also high at a value of 1845. The head restraint reduced the acceleration to 900 m/s^2 (a reduction of about 72%), and the HIC_{15} to 346 (reduction of about 81%). Therefore, it was confirmed that the head restraint reduces the severity of the impact on the head in its collision with the road surface.

4.2. Car-to-cyclist collision tests

4.2.1. Kinematic behavior of dummies

In all the tests, the adult dummy rotated toward the hood and impacted the rear of the hood while sliding over it, while the lower half of the dummy was pushed in the car's direction of travel after its impact by the front of the car. After that, as the car braked, the adult dummy fell to the front of the car and collided with the road surface. The kinematic behavior of the adult dummy, which was observed in this study on a bicycle equipped with a child seat, was similar to that in single-cyclist collisions against a car (Maki et al., 2003; Otte, 1980; Otte, 1989).

The kinematic behavior of the child dummy changed significantly depending on whether the dummy was fastened by a seat belt or not. In Tests 1 and 2 in which the seat belt was not fastened, after impact by the front of the car, the child dummy was ejected out of the child seat while rotating toward the hood. Afterward, the dummy collided with the hood and then fell onto the road surface. However, in Tests 3 and 4 in which the seat belt was fastened, the child dummy having been restrained by the seat belt, rotated along with the bicycle toward the hood while continuing to be sitting on the child seat. Afterward, the dummy collided with the hood and then fell onto the road surface. The dummy was restrained in the child seat, and it moved together with the bicycle from the start of the collision until the crash event was completed on the road. The difference in the kinematic behavior of the child dummy depended on the state of whether the seat belt was fastened (or not) and was similar to that observed in rear-end collision tests (Terashima et al., 2018).

In Tests 1 and 2, the child dummy was thrown above the hood due to the collision with the car; but in Tests 3 and 4, the child dummy, which was restrained in the child seat by the seat belt, was pushed forward by the car. As a result, the child dummies reached higher height positions in Tests 1 and 2 than in Tests 3 and 4 (Fig. 8). It is likely that the risk of injury in Tests 1 and 2 is higher than that in Tests 3 and 4 because the impact velocity with the road surface is higher when the child dummy falls from a higher height position.

In this study, there was no significant difference in the collision of the head with the car, and the effect of the head restraint was not observed. In the collision with the car, the head of the child dummy hit the hood in Tests 1 to 3; but in Test 4, the child dummy was restrained by the seat belt in the child seat with a head restraint, and the head hit the hood via the left arm. Thus, the head restraint did not affect the collision of the child dummy with the hood. This is because the bicycle was moving in

Fig. 8. Approximate highest height position that the child dummy reached. The red line shows the top height of the car's side mirror.

Test 4, and after the impact between the bicycle and the car, the child dummy moved in a diagonally forward direction where the head moved out from the head restraint.

In the collisions with the road surface, the head directly impacted the road surface in Tests 1 to 3, whereas the head restraint prevented the head from directly impacting the road surface in Test 4. This suggests that the head restraint may prevent the head from directly colliding with the road surface in the case that the child is restrained by the seat belt in a child seat.

4.2.2. Child injury risk

This study mainly focused on the risks of head injuries, as many children who are carried on bicycles incur head injuries in traffic accidents (Terashima et al., 2015). By comparing the impact of the child dummy with the car and the impact with the road surface, the maximum head resultant acceleration and HIC_{15} were highest in the impact with the road surface in Tests 1, 3, and 4 and in the impact with the car in Test 2 (Table 4). In the rear-end collision of a bicycle equipped with a child seat (collision speed was 19 km/h) (Terashima et al., 2018) and in a single-seat bicycle collision at a similar collision speed (Omoda and Konosu, 2015), it was shown that the head injury risk in the impact with the road surface is higher than in the impact with the car, and the same tendency was observed in the side collisions with the car in this study. In Tests 1, 3, and 4, the head impacted the road surface at a relatively early stage during the road impact of the child dummy; whereas in Test 2, the pelvis first impacted the road surface, and the head then impacted the road surface after the fall speed had decreased. This suggests that the posture of the child dummy while falling onto the road surface greatly affects the head injury risk.

The kinematic behavior of the child dummy differed depending on the seat belt use conditions, but the conditions of using the seat belt and having a head restraint did not significantly affect the maximum value of the head resultant acceleration and HIC_{15} in a collision with the car.

In the condition that the seat belt was not fastened in Tests 1 and 2, the child dummy independently fell onto the road surface; and in the condition that the seat belt was fastened in Tests 3 and 4, the child dummy and the bicycle fell together onto the road surface. In either condition, it is expected that the child would fall from the air and collide with the road surface in various postures, thereby leading to a child to be injured in various regions of the body. However, in the condition that the seat belt was fastened in the tests, the child dummy remained restrained in the child seat, and the pelvis and back did not directly impact the road surface, thereby the seat belt would reduce the risk of injuries except for that to the head.

In the collisions with the road surface, it was difficult to make simple comparisons because the kinematic behavior of the child dummy differed for each test. However, in Tests 1 and 3, the kinematic behaviors of the head impacts to the road surface immediately after the upper limbs of the child dummy had made their impact were similar, so making a comparison was possible. The maximum head resultant acceleration and HIC_{15} were higher in the condition that the seat belt was not fastened (Test 1) than in the condition that the seat belt was fastened (Test 3). This is because the vertical component of the head impact velocity with the road surface was larger in Test 1 (6.1 m/s) than in Test 3 (2.8 m/s), even though the resultant velocity was comparable (Table 5). It is probable that this difference in the vertical velocity component was caused by the fact that the child dummy reached a higher height position after the collision with the car in the condition that the seat belt was not fastened than in the condition that the seat belt was fastened.

Another effect of the seat belt during the collision with the road surface also has been previously reported by Terashima et al. (2018). When a bicycle first collided with the road surface in the condition that the seat belt was fastened and the child dummy was restrained in the child seat, the impact speed of the child dummy decreased because the bicycle impact absorbed some of the motion energy of the child dummy. In Test 3, the child dummy's head impacted the road surface before the impact of the bicycle with the road surface, thus this effect of the bicycle impact absorbing the energy of the child did not occur. However, in Test 4, the bicycle collided with the road surface before the impact of the child dummy with the road surface, and it is possible that the impact speed of the child dummy was decreased.

However, there is a dangerous case when the seat belt is fastened, and the child dummy is restrained in the child seat. If the child dummy collides with the road surface before the collision of the bicycle with the road surface as in Test 3, the weight of the bicycle might be added to the collision area of the child dummy, which might lead to a higher risk. The maximum head resultant acceleration was smaller in Test 3 than in Test 1, but the neck was greatly flexed due to the nature of the head impact with the road surface (Fig. 9), and a serious injury would be expected. Therefore, it is necessary to take measures to prevent children on bicycles from colliding with the road surface before the occurrence of the collision of the bicycle with the road surface.

It was only in Test 4 that the head restraint prevented the head from direct contact with the road surface. From the results of the fall test, it was confirmed that the head restraint reduced the maximum head resultant acceleration by 72% in the collision with the road surface, and it was expected that the severity of the impact was also reduced in Test 4. In addition, even if the child collides with the road surface before the collision of the bicycle with the road surface as occurred in Test 3, by using a head restraint that is higher than the top of the child's head and by increasing the area with which the child seat covers the child, it is expected that the child would not collide with the road surface during a collision of the bicycle with the road surface. Such measures are

Table 5
Impact speed and impact angle of the child dummy's head in the collision with the road surface.

Test No.	Impact speed [m/s]			Impact angle [degrees]
	Resultant	Horizontal direction	Vertical direction	
1	8.4	5.7	6.1	47
3	8.0	7.5	2.8	20

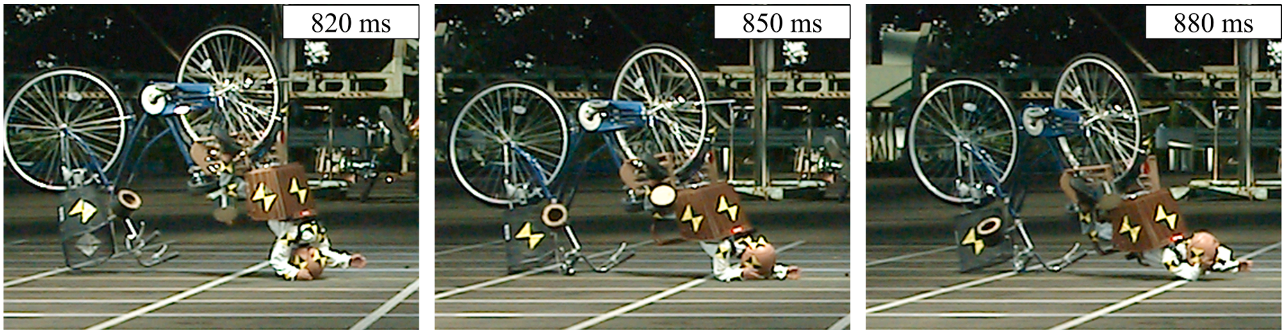


Fig. 9. Collision of the child dummy with the road surface in Test 3.

expected to reduce the risk of neck injuries in situations like that in Test 3.

Based on the results of the tests, it was found that using a child seat with a head restraint and using the seat belt can reduce the risk of injury to children in a collision with the road surface. Of course, using a helmet is expected to further reduce the risk of head injury since the effectiveness of helmets has been confirmed in many studies (Bambach et al., 2013; Mizuno et al., 2014; Omoda and Konosu, 2016).

5. Limitations of the study

A Hybrid-III dummy was used as the bicycle occupant in this study. It is not clear if it is suitable for use as the bicycle occupant to investigate bicycle accidents since the Hybrid-III dummy was developed as an automobile occupant (Foster et al., 1977; FMVSS 208 49 CFR Part 572).

In this study, the test car was a sedan type, and the target collision speed of the car was 8.3 m/s (30 km/h). If the front shape and the collision speed of the car are the same as that in the collision tests, the kinematic behavior of the cyclists and children may be similar to that observed in the results of this study. However, since the front shape and collision speed of a car have a great influence on the kinematic behavior and therefore the injury of cyclists and pedestrians (Ravani et al., 1981; Simms and Wood, 2009), it may also affect the kinematic behavior and resulting injuries of children on bicycles. It is necessary to study other front shapes and other collision speeds in the future.

The risk of head injury of children was evaluated based on head acceleration and HIC_{15}. Since there is a factor that head injury is caused by the head angular acceleration such as diffuse brain injury, it is necessary to study the influence of angular acceleration in future research.

In a collision between a car and a bicycle, a cyclist is expected to fall on the road surface in various postures, so further experiments are necessary, and the results of this study cannot be generalized.

6. Conclusions

In this study, fall tests of the child dummy were conducted to evaluate the effect of the presence or absence of head restraints with child seats, and it was shown that head restraints reduce the impact on the head in impacts with the road surface.

Side collision tests between a car and a bicycle equipped with a child seat were conducted, and the effects of the seat belt and the head restraint of the child seat were investigated. The following conclusions were drawn.

The kinematic behavior of the child dummy changed significantly based on whether the seat belt was fastened around the dummy or not. In the condition that the seat belt was not fastened, after impact by the front of the car, the child dummy was ejected out of the child seat while rotating toward the hood. However, in the condition that the seat belt was fastened, the child dummy moved together with the bicycle while remaining seated on the child seat from the start of the collision and through the entire crash event ending on the road surface.

It was found that the risk of head injury to child dummy tended to be higher in collisions with the road surface than in impacts by and to the cars, and the severity depended on the body posture of the child dummy when falling onto the road surface.

In the side collision with the car, the impact on the child dummy's head against the car body was not significantly different with or without the use of a seat belt or a head restraint.

It was found that using the seat belt and the head restraint reduced the risk of injury to the child dummy in the collisions with the road surface. However, if a child impacts the road surface before the occurrence of an impact of the bicycle with the road surface, the risk of injury may increase due to the additional weight of the bicycle on the child. It is necessary to take measures to prevent such serious injuries, such as increasing the area with which the child seat and the head restraint cover the child.

CRediT authorship contribution statement

Takaaki Terashima: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Kenshiro Kato:** Methodology, Investigation, Resources. **Ryo Oga:** Investigation, Resources, Data curation, Funding acquisition. **Nobuaki Takubo:** Investigation, Resources, Funding acquisition. **Koji Mizuno:** Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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