THE CRASHWORTHINESS OF MINICARS IN FRONTAL IMPACT TESTS

Koji Mizuno
Nagoya University
Yuji Arai
Japan Automobile Research Institute
Naruyuki Hosokawa
National Traffic Safety and Environment Laboratory
Japan
William Hollowell
WTH Consulting LLC
United States

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ABSTRACT

In Japan, the number of minicars is increasing due to market demands resulting from environmental and economic concerns, and constitutes 32% of the registrations among passenger cars (2012). The safety of the minicar for various crashes is a technological challenge due to its small size and mass. In this paper, the crashworthiness of minicars was investigated and the issues that should be addressed are discussed. The crash pulse, deformation, and dummy responses of minicars were examined for various frontal impact tests: full-width rigid barrier (FWRB), offset deformable barrier (ODB), full-width deformable barrier (FWDB), and car-to-car tests.

In the FWRB tests, the car accelerations were high and large crash loadings were applied to the occupants. The dummy injury measures were less than injury thresholds because of the high performance of occupant restraint systems: the early and timely restraint system. In the FWDB tests, the deformation mode was relatively comparable to that in the car-to-car tests, and dummy injury measures were higher than those in the FWRB tests. An analysis using a simple spring-mass model indicated that a later restraint trigger time in the FWDB test led to high injury measures of the occupants.

In the ODB tests, the passenger compartment was intact for all of the tested minicars. Since the car acceleration in the ODB test was lower than that in the FWRB tests, all of the injury measures of the driver dummy in the ODB tests were smaller than those in the FWRB tests except for the tibia index. In the car-to-car tests, though the minicar has a single-load path, the structural interaction was acceptable since the engine was located forward in the vehicle and interacted with structures of the other car. The passenger compartments of the minicars were intact and injury measures were lower than the injury thresholds until the loading on the vehicles reached the NCAP crash severity level. The crashworthiness of Japanese minicars could be representative of the safety of future mini electric vehicles.

INTRODUCTION

In Japan, a category of mini vehicle has been introduced as of 1949 in order to disseminate more detailed information of passenger cars to the public. Since then, the specifications of the mini vehicle were revised several times, and in 1998 the specifications stated that the engine dimension was equal or less than 0.660 l; and that the length, width, and height were equal or less than 3.4 m, 1.48 m, and 2.0 m respectively (Road Trucking Vehicle Act). According to the Automobile Inspection and Registration Information Association, the number of registered vehicles is 79,871,540 in Japan on November of 2012. Among them, the number of mini vehicles including minicars and mini trucks is 28,274,642 (35.4%). For passenger cars, the number of registered minicars and other size cars is 19,216,040 (32.4%) and 40,184,214 (68.6%), respectively. This trend of a large portion of minicar registration is anticipated to continue especially when the economic situation is taken into consideration.

The crashworthiness of the minicar has been addressed in the regulation and New Assessment Car Program (NCAP). Since 1994, a full-width rigid barrier (FWRB) test has been introduced to passenger cars in the Japanese regulation. At that time, the test velocity of the minicars was 40 km/h. In 1998, the velocity of minicars was increased to 50 km/h, and the minicar dimensions were extended to satisfy this severe impact condition. The Japan New Car Assessment Program (JNCAP) started at 1995, and the FWRB tests at 55 km/h were conducted though minicars were not included among the tested cars. The minicars have been involved in JNCAP tests as of 1999. In 2000, JNCAP started an overall more comprehensive evaluation test program. The tests consisted of the FWRB (55 km/h) tests, the offset deformable barrier (ODB) tests (64 km/h), and the side impact test (55 km/h). In 2007, the ODB tests at 56 km/h (ECE R94) were applied to passenger cars including the minicars in the Japanese regulation. At present, the same crash tests and their requirements are applied to minicars as to the other passenger cars.

National accident data (2009) show that the probability of fatal injury to occupants in minicars (0.23%) was comparable to that of other size passenger cars (0.22%) in all accidents. However, in car-to-car collisions, the injury risks to occupants are higher for minicars as compared to larger size cars. The Institute of Traffic Accident Research and Data Analysis (ITARDA) investigated the injury risk to drivers in vehicle-to-vehicle collisions classified from vehicle category and driver age [1]. The number of fatal and serious injuries to drivers of minicars constitutes 24.3% of these injuries among all vehicle types.**Error! Reference source not found.** Figure 1 shows the probability of fatal and serious injuries to drivers. They are high for minicars, particularly for elderly people.

In this research, the crashworthiness of minicars in various front impact tests was examined. The test data included in the analysis were from the FWRB and ODB tests conducted by JNCAP from 2008 to 2011, the full-width rigid barrier (FWDB) and car-to-car crash tests conducted by both the Ministry of Land, Infrastructure, Transport and Tourism (JMLIT) and the Japan Automobile Manufacturers Association (JAMA).

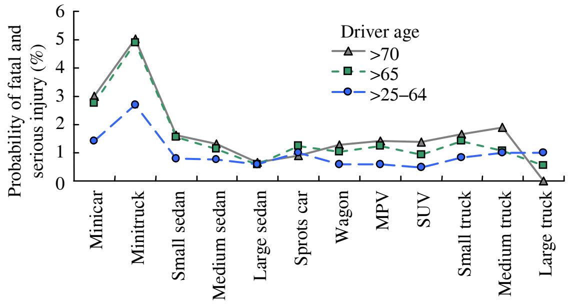
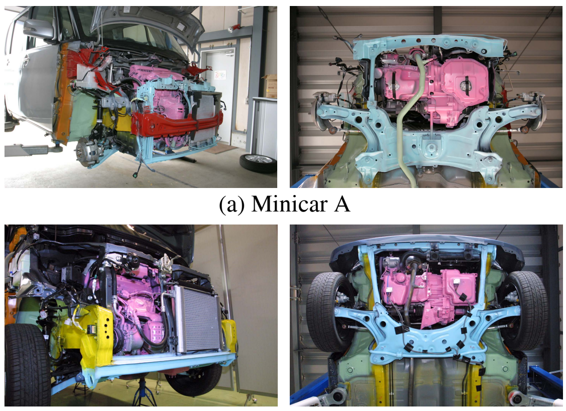


Figure 1. The probability of injuries to drivers for vehicle types in vehicle-to-vehicle collisions [1]

STRUCTURES

Though the engine compartment of the minicars is short, there are no significant differences in the structures of minicars as compared to other size cars (Figure 2). The minicar A has front rails connected by the bumper cross beam. The lower cross member of the driver side is connected with the suspension member by a tube. The minicar B does not have a bumper cross beam; however, the tall front rails of the minicar B are connected by the stiff lower cross member. The lower cross member is connected by tubes with the suspension member. In general, the engine of minicars is located forward, and the air conditioner compressor and the catalytic device (which are stiff structures) are installed in front of the engine. In car-to-car crashes, they can interact with structures of other cars.

The height of the front rail and subframe of cars are shown in Figure 3. The cross section of the front rails of the minicars are included within the Part 581 zone, but are inclined to be lower than that of cars of larger size. The lower front rails of the minicars could cause insufficient energy absorption of the front rails, and lead to underride in car-to-car crashes.



(a) Minicar A

(b) Minicar B

Figure 2. The structure of minicar [2]

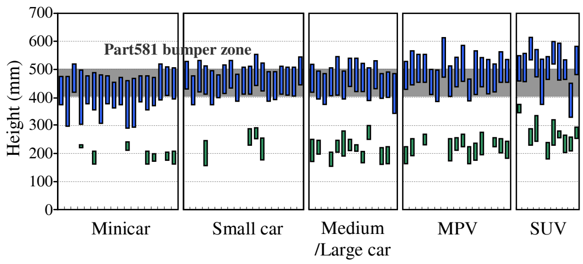


Figure 3. The ground clearance of front rails (blue bars) and subframes (green bars)

FWRB TESTS

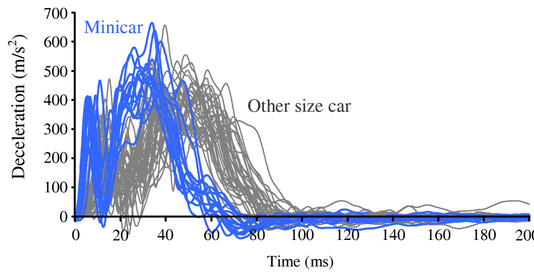
In the FWRB tests, the acceleration of the passenger compartment is high and provides a demanding environment for the evaluation of the performance of the restraint system.

Vehicle Acceleration

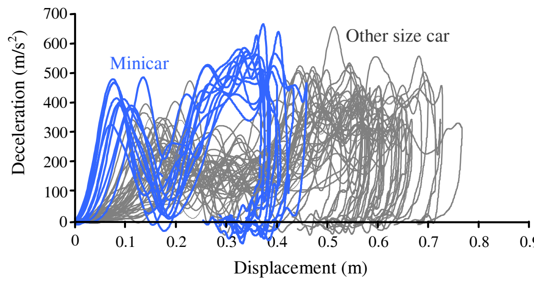
The vehicle deceleration-time histories in the FWRB tests are shown in Figure 4(a). The deceleration was measured at the driver side B-pillar. There are two stages in the vehicle deceleration. The first stage is characterized by the collapse of the front rails, and the second stage is characterized by the deformation of the structures behind the engine including passenger compartment. The average deceleration of minicars over the crash pulse time duration is about 300 m/s^2 and that of other cars is 180 m/s^2. The time duration of the mini cars (60–80 ms) is shorter than that of other size cars (80–100 ms). The deceleration-displacement curves are shown in Figure 4(b). The front rail axial collapses within 0.2 m of the vehicle deformation, and the maximum minicar deformation is 0.4 m. For other size cars, the maximum deformation is distributed from 0.5 to 0.7 m. The high decelerations of the minicars indicate a high stiffness of front structures relative to their mass.

Occupant Response

The decelerations of a vehicle and driver dummy (Hybrid III AM50th) in the FWRB tests are compared for a minicar and a small sedan in **Error! Reference source not found.**. As the vehicle deceleration of the minicar is higher, the dummy chest and head decelerations in the forward direction (x) are also higher for minicars. The seatbelt pretensioner activates at 12 ms for the minicar and at 18 ms for the small sedan. In general, the time to fire (TTF) of the restraint system is 9–10 ms for minicars, whereas it is 15–18 ms for other size cars. Therefore, the early TTF is one of key parameters to consider for optimizing the occupant protection provided by minicars.



(a) Vehicle deceleration-time history



(b) Vehicle deceleration-displacement curve

Figure 4. Vehicle deceleration-time history and deceleration-displacement curve in FWRB tests at 55 km/h

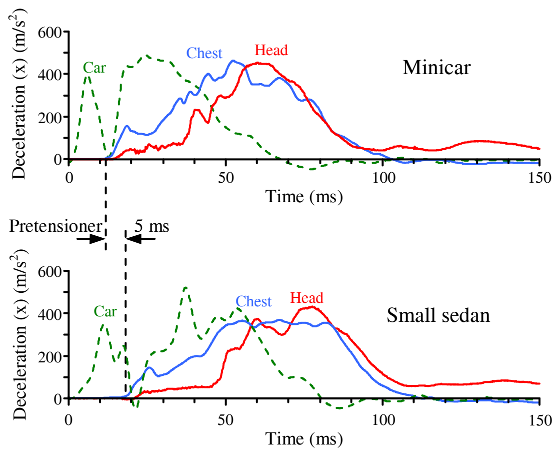


Figure 5. Vehicle and driver dummy deceleration in the forward direction vs. time for a minicar and small sedan in FWRB tests at 55 km/h

In frontal crashes, the occupant motion energy is absorbed by the restraint system energy and vehicle deformation energy. The sum of restraint system energy and ridedown energy is equal to the initial kinetic energy. When normalized by the occupant mass, this can be written as:

$$V_0^2/2 = e_{rs} + e_{rd} \quad (1)$$

where V_0 is the initial velocity, e_{rs} is the restraint energy density and e_{rd} is the ridedown energy density. The ridedown efficiency μ that indicates that the ratio of vehicle deformation energy to initial occupant motion energy, is defined as [3]:

$$\mu = \frac{\int_0^{X_{max}} (-\ddot{x})\, dX}{V_0^2/2} \quad (2)$$

where x and X is the chest displacement and the vehicle displacement, respectively. Figure 6 shows the ridedown efficiency calculated using the chest acceleration of driver dummy. The ridedown efficiency decreases with the average deceleration of the vehicle. The ridedown efficiency of minicars is distributed from 0.2 to 0.35, whereas that of other size cars is distributed from 0.3 to 0.65. Accordingly, a greater portion of the initial occupant motion energy should be absorbed by the restraint system in minicars.

Figure 7 provides a plot of the chest deceleration of the driver dummy vs. the chest displacement relative to the vehicle. Two minicar models are shown in addition to the other size cars. The area surrounded by the acceleration and displacement curve (up to the point of maximum displacement) represents the restraint energy. This area tends to be larger for minicars because the ridedown energy of the minicar is large. Both minicars shown is this plot have a high chest deceleration since their seatbelt force limiters have been designed with higher force levels (two stages: 5–7 kN, 3–5 kN) in order to absorb the restraint energy within the limited chest deceleration and displacement available. The minicar C has a double seatbelt pretensioner, so that the initial chest deceleration level is high. The minicar D has a steering axis collapse system to absorb the energy, and as a result provides a larger chest displacement. Thus, with these design features, the seatbelt system of the minicars have been optimized for the high decelerations associated with the FWRB tests.

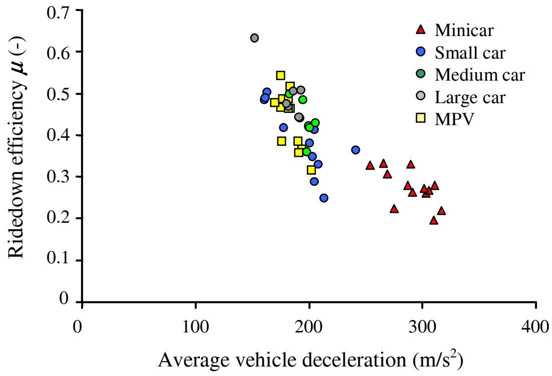


Figure 6. Ridedown energy calculated by driver chest acceleration in forward direction in FWRB tests

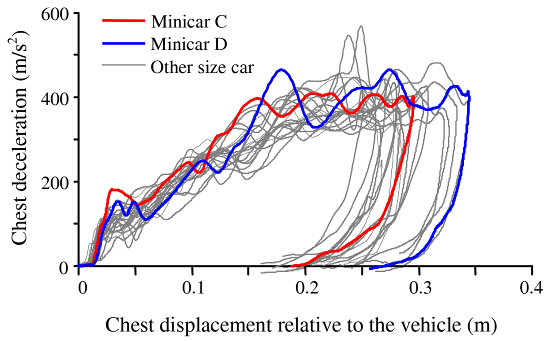


Figure 7. Driver dummy chest forward deceleration vs. chest forward displacement relative to the vehicle

In Figure 8, the head forward decelerations are shown for the minicars E and F, and the small sedan. The head deceleration is high for minicar because of high vehicle deceleration. As shown in Figure 8, the airbag of the minicar E could absorb the head motion energy effectively whereas the head deceleration of minicar F was delayed and the ensuing head deceleration was higher. For a minicar, the airbag could bottom out in more severe vehicle decelerations than experienced in NCAP tests.

The injury measures of the driver dummies are shown in Figure 9. It is found that the injury measures are affected by the upper and the lower limits set by NCAP. The chest acceleration and deflection of minicars tend to be high compared to other size cars. The tibia index is also high because of this high deceleration though the intrusion is small.

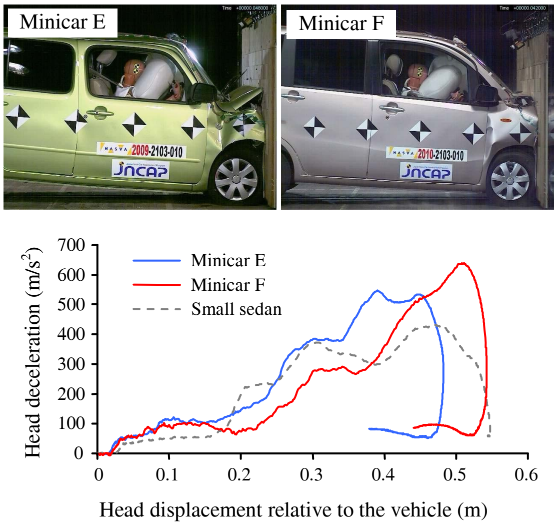


Figure 8. Head deceleration in FWRB tests

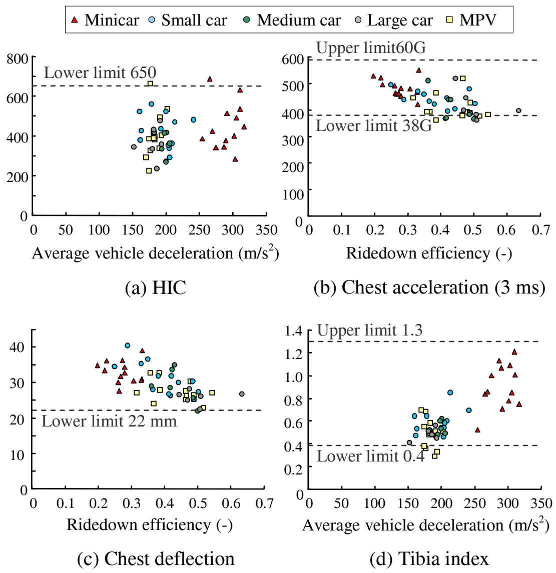


Figure 9. Injury measures of the driver dummy in FWRB tests (55 km/h)

FWDB TESTS

In the FWDB tests, the vehicle is impacted into a honeycomb barrier face that consists of two-layers (each layer of 150 mm depth) [2]. The honeycomb is effective in making the deformation mode of the vehicle structures in this test comparable to that in car-to-car crashes, and can mitigate the engine dump force which is a significant contribution toward evaluating the structural force distribution with the load cell wall. The honeycomb face had little effect on the vehicle deceleration pulse, so that the FWDB test also provides a high deceleration test from which to evaluate the performance of the restraint system.

Vehicle Deformation and Acceleration

Figure 10 presents the deformation of minicars after the FWDB tests. The front structures does not deform uniformly in the FWDB test because of the honeycomb resistance force. The stiff front rails penetrated into the honeycomb, whereas the weak bumper cross beam could not push through the honeycomb to the same level as the front rails. The other structures deformed and the engine moved rearward. Accordingly, the intrusion into the passenger compartment of the minicars was larger in the FWDB tests as compared to that in the FWRB tests. In car-to-car crashes, the front structures also do not deform uniformly since the car crashes into structures with various stiffnesses. It has been determined that the structural deformation mode in the FWDB test is more comparable to that in car-to-car crashes as compared to that in the FWRB test.

Figure 10. The deformation of minicars in a FWDB test (55 km/h)

The accelerations of the vehicle and the occupant chest in a minicar are shown in Figure 11 for a FWRB and DWDB test (impact velocity was 55 km/h). The crash pulse of the vehicle in the FWDB test is rear-loaded as compared to that in FWRB test. In the FWRB tests, a high initial acceleration occurred due to the immediate axial loading and collapse of the front rail. On the other hand, in the FWDB test the initial acceleration was low since the axial collapse of the front rails did not occur to the degree experience in the FWRB test. The TTF, based on a sensor algorithm which activates the seatbelt pretensioner and the airbag deployment, would late in the FWDB tests if the sensor algorithm was designed to activate by detection of an initial high acceleration caused by the front rail axial collapse in an FWRB test.

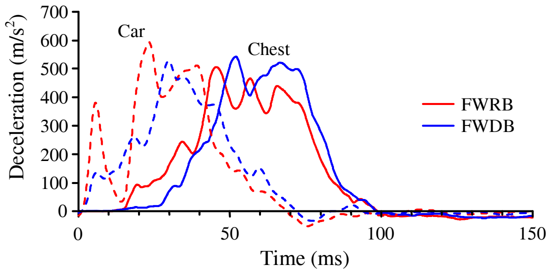
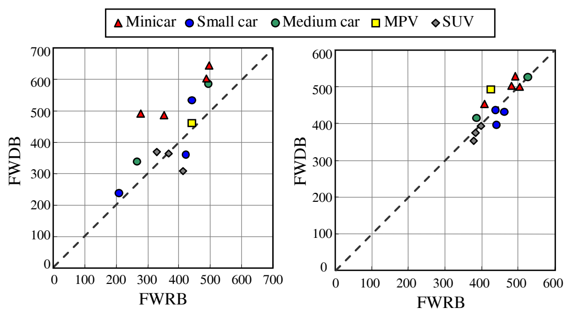


Figure 11. The vehicle and the chest deceleration in forward direction of a minicar in FWDB test (55 km/h) and FWRB test (55 km/h)

Occupant Response

The vehicle acceleration in the FWDB as well as the FWRB tests provides a large loading on occupant dummies provides a severe crash condition with which to evaluate the performance of restraint system. The injury measures of the driver dummies (Hybrid III AM 50th) between the FWRB and the FWDB tests were compared. Figure 12 shows the HIC and the chest acceleration. In general, these acceleration-base injury measures of minicars in the FWDB tests are higher than those in the FWRB tests. The injury measures of the lower extremities, such as the femur force and tibia index, were comparable between the two tests though they were distributed significantly (not shown in Figure 12).

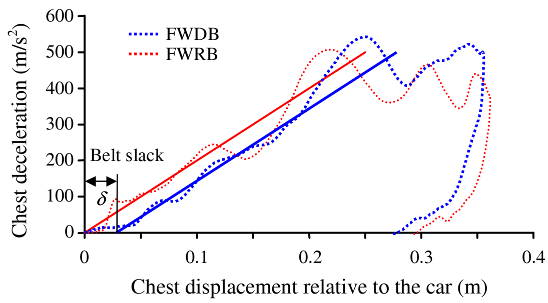


(a) HIC (b) Chest 3ms (m/s^2)

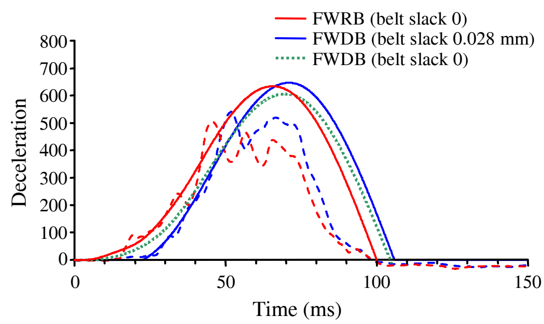
Figure 12. The comparison of injury measures of driver dummies in FWRB and FWDB tests

In order to understand the reason that led to the higher injury measures of the dummies in minicars in the FWDB tests, a simulation using a simple spring-mass model was carried out. The restraint spring characteristics were estimated from the Hybrid III chest forward acceleration and the chest displacement relative to the vehicle (Figure 13(a)). The stiffness of the restraint system spring normalized by the occupant mass (*k*/*m*) was approximated from the initial acceleration-displacement curve. In the FWRB test, the chest acceleration increased with chest displacement since the seatbelt pretensioner activated immediately. The TTF was later in the FWDB test, and this delay was incorporated as the slack in the seatbelt spring (0.028 mm).

The vehicle accelerations measured in the FWRB and FWDB tests (see Figure 11) were applied to the simple-mass spring model as an acceleration field. Figure 13(b) shows the occupant acceleration calculated from the simulation. The initial acceleration agrees with that in the experiments up to the time when the seatbelt force limiter started to work. Accordingly, the loading on the dummy can be estimated with the maximum deceleration of the occupant mass in the model. The maximum occupant decelerations were 632 m/s^2 and 647 m/s^2 in the models of the FWRB and FWDB, respectively. When the seatbelt slack was set to zero in the FWDB test, it was found that the maximum deceleration dropped to 607 m/s^2. Consequently, the chest acceleration of the Hybrid III in a FWDB test can be higher than that in a FWRB test because of the late TTF, even though the vehicle crash pulse in FWRB test is more severe for occupants.



(a) Occupant restraint characteristics



(b) Occupant response

Figure 13. The chest forward acceleration in FWRB and FWDB based on simple spring-mass model

The delay in the initiation of the airbag deployment led to a higher pressure of the airbag because the forward moving dummy resulted in the airbag deployment space being smaller. The airbag force was exerted on the dummy face in the upper direction. The neck rearward moment (My) increased, and the neck shear force (Fx) was higher. In addition to the deceleration force of the airbag, this neck shear force (Fx) that was applied to the head in the rear direction induced a high deceleration of the head, which in turn led to high HIC value. The high airbag pressure also resulted in a large rebound of the dummy head, and caused the time duration of the head acceleration to be longer. These also contributed to the higher HIC.

There was an observed trend that the TTF of minicars was late in the FWDB tests. This TTF was compared to those of the FWRB, ODB, and car-to-car tests. The vehicle deceleration pulse depends on the crash configuration, and it was necessary to take the vehicle deceleration-time history into account when examining whether the TTF is determined to be at the proper time. Therefore, the “5 inch (127 mm) – 30 ms” criterion was used to evaluate the airbag deployment start time. The unbelted occupant displacement (x) with respect to the vehicle is calculated as [3]:

$$x = -\int_0^t \int_0^t a(t)\,dt\,dt \qquad (3)$$

where $a(t)$ is the occupant acceleration. The unbelted driver will not be injured by a deploying airbag if the airbag deployment is completed by the time when the displacement of the unbelted driver (x) reaches 127 mm. Taking the airbag inflation time into account, the TTF should be 25 to 30 ms before this time. Figure 14 provides a plot of the airbag deployment start time (t_s) vs. time when the unbelted occupant reaches 127 mm ($t_{5''}$) for minicars in FWDB, FWRB, and car-to-car crash tests. The time difference from when the airbag starts to deploy to when the unbelted occupant reaches 127 mm (t_s–$t_{5''}$), can be a measure of the delay of the TTF or the airbag deployment initiation time. From Figure 14, it is found that the airbag deployment start time (t_s–$t_{5''}$) in FWDB tests is between the FWRB tests and ODB tests, and is later than that in the car-to-car crashes with a large overlap ratio (>50%). It is likely that the airbag deployment start time (t_s–$t_{5''}$) is more dependent on crash configuration (overlap ratio).

The late TTF of minicars in the FWDB tests could be improved if the sensor locations and the vehicle structures were improved. This modification will contribute to ensure an appropriate airbag deployment initiation time in the cases where the structural interaction is not acceptable. However, the effectiveness of this modification would need to be verified because the late TTF of minicars in the FWDB tests might not reflect the TTF in car-to-car crashes.

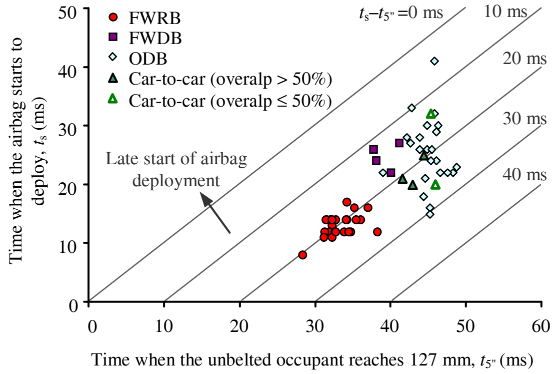


Figure 14. Minicar crash tests shown by airbag deploy start time and the time when the unbelted occupant reached 127 mm

ODB TESTS

In the ODB tests, the vehicles side are impacted on the driver side into an EEVC barrier with 40% overlap of vehicle width. The ODB tests can be used to evaluate the integrity of the passenger compartment. Generally, the average acceleration of the vehicle model in the ODB tests is lower and proportional to that in the FWRB tests. The stiffness mismatch between minicars and other size cars can be observed relative to the honeycomb stiffness. For minicars, the honeycomb still deforms even during the phase of the passenger compartment deformation, and after the test there remains residual crushable depth available in the honeycomb. This situation is different from other size cars for which the honeycomb bottoms out completely. Particularly for a large car, the honeycomb bottoms out even when only the structure in front of the engine is deforming.

Figure 15 shows the relation between the firewall intrusion and the maximum vehicle deformation. Because of the limited size of the engine compartment, the firewall intrusion of minicars increases from the maximum vehicle deformation of 0.8 m, and it exceeds 0.1 m with a vehicle deformation of 0.9 m. For small cars, the firewall intrusion tends to be large; however, for medium and large cars, the firewall intrusion increases as the maximum vehicle deformation is 1.2 m or more.

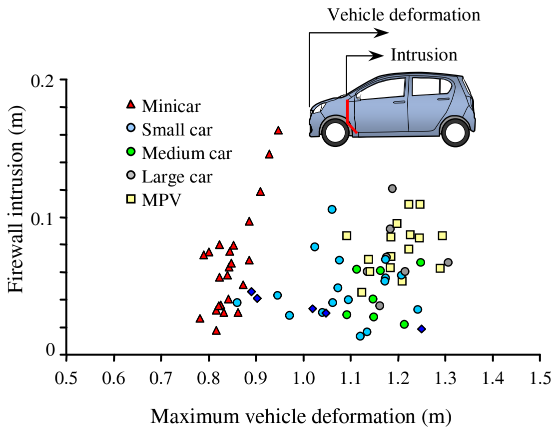


Figure 15. The intrusion into the passenger compartment in ODB tests at 64 km/h

The injury measures of the driver dummy (Hybrid III AM50th) in the ODB tests are shown in Figure 16. Several parameters were examined that could relate with the injury measures. The average vehicle deceleration, chest acceleration and chest deflection from the FWRB tests, and the firewall intrusion were selected to determine if they had a correlation with each injury measure. The injury measures in the ODB tests are lower than those in the FRWB tests, except for the tibia index. There is a tendency that the chest acceleration and chest deflection in the ODB tests are proportional to and lower than those in the FWRB tests. The tibia index is higher as the firewall intrusion is 0.12 or more, which corresponds to maximum vehicle deformation of minicar 0.9 m (see Figure 15). The tibia index in the ODB tests is higher than that in the FWRB tests because of this large intrusion.

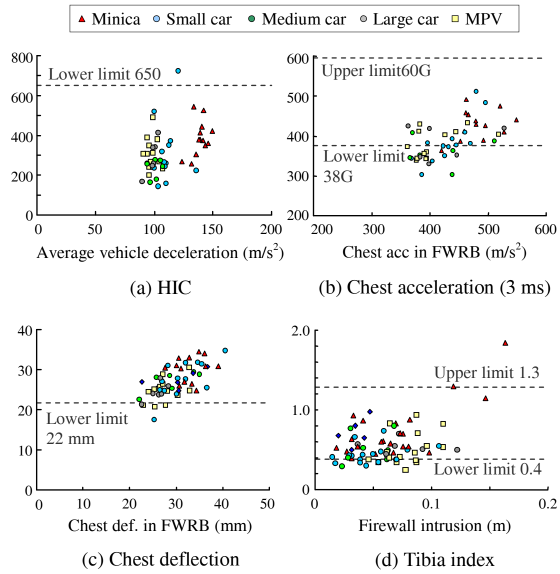


Figure 16. Injury measures of driver dummy in ODB tests (64 km/h)

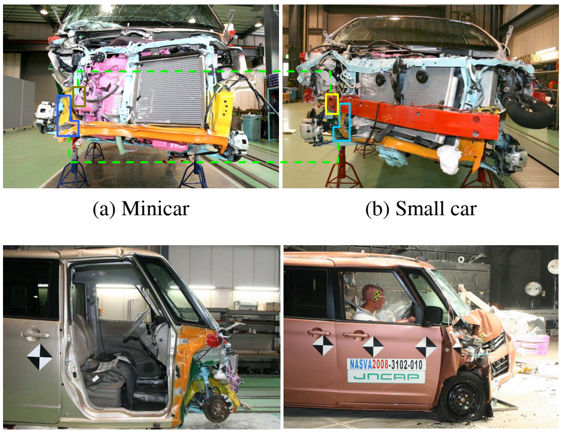
CAR-TO-CAR CRASH TESTS

Three car-to-car crash tests including minicar were reviewed. Table 1 presents the crash test conditions. In addition to the closing velocity, the velocity change of the minicar from the initial velocity V_{10} to the common velocity V_c during impact is tabulated to compare the crash severity with NCAP (55 km/h).

Table 1. Crash condition in car-to-car tests

No.	Crash configuration	Minicar (test mass)	Opposite car (test mass)	Closing vel. ($V_{10} - V_c$)
1	Offset (overlap 50%)	Minicar 1120 kg	Small car 1313 kg	100 km/h (55.5 km/h)
2A 2B	Full-width 2A: original ride height 2B: front rail height match	Minicar 1024 kg	Large car 1695 kg	100 km/h (63.3 km/h)
3	Overlap 85%	Minicar 900 kg	MPV 1760 kg	80 km/h (53.4 km/h)

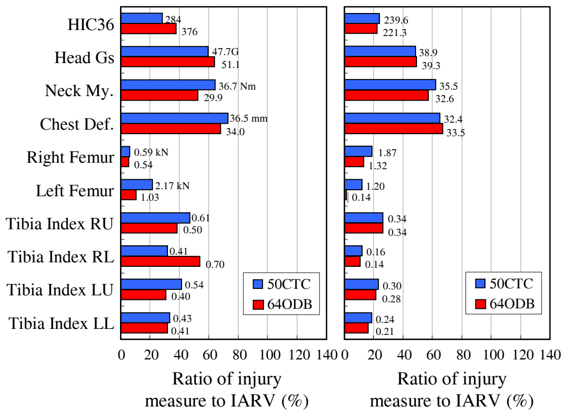
In Test 1 [2], the minicar was impacted into a small car. The velocity change of the minicar was 55.5 km/h, which is similar to the NCAP impact severity (55 km/h). The front rail of the minicar made contact with the bumper cross beam of the small car; whereas the front rail of the small car contacted the air conditioner compressor of the minicar. The front rails of both cars deformed efficiently, and as a result the passenger compartment of the minicar was intact. The injury measures of the driver and the front passenger dummies (Hybrid III AM50th) in the minicar were compared between the car-to-car test and the ODB test (64 km/h) in Figure 18. All of the injury measures of the driver dummy in the minicar in the car-to-car tests were similar to those in the ODB tests 64 km/h, and were less than the injury assessment reference values (IARVs).



(a) Minicar (b) Small car

(c) Minicar (d) Minicar in ODB 64 km/h

Figure 17. The deformation of minicar in crash into a small car (Test 1)



(a) Driver dummy (b) Front passenger dummy

Figure 18. The injury measures of minicars in car-to-car test (Test 1) compared with those in ODB test

The minicars and the large cars were impacted at the original ride height (Test 2A) and front rail height matching (Test 2B) [5]. In the original ride height, the front rails of both cars passed by each other, and the upper area of the minicar was engaged. The fascia moved rearward and the steering axis rotated upward. The force displacement characteristics in Test 2B were comparable with those in the FWRB tests at 55 km/h (Figure 19). Because of the mass ratio of the two colliding cars, the deceleration was higher for the minicar, and it was less for the large car than occurred in the FWRB tests. However, the car deformation in the car-to-car tests can be predicted from the crash test against a wall test since the crash interface behaves like a wall if the structural interaction is good. These tests demonstrated the effectiveness of front rail height matching.

The injury measures of the driver and the front passenger dummies (Hybrid III AM50th) were compared for the original ride height and for height matching. In Test 2A (original height), the large intrusion led to large femur force and tibia index. The steering axis upper rotation resulted in a large chest acceleration and neck extension moment.

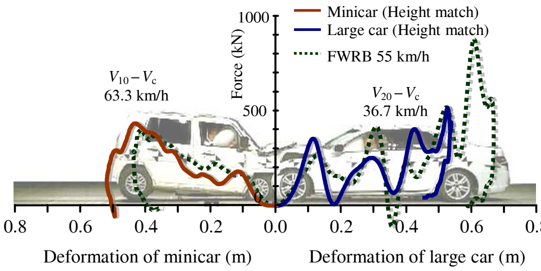
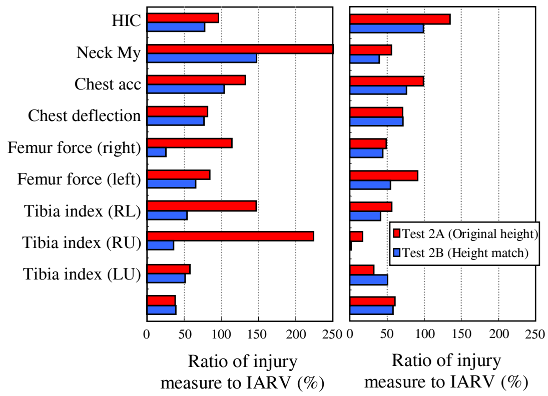


Figure 19. The deformation of minicar in crash into a small car (Test 1B: front rail height matching)



(a) Driver dummy (b) Front passenger dummy

Figure 20. The injury measures of minicars in car-to-car test (Test 2A and 2B)

Test 3 was conducted to perform an accident reconstruction for a frontal collision between minicar and multi purpose vehicle (MPV). The minicar and the MPV were impacted with an 85% overlap of the front passenger side of the minicar. A Hybrid III AF05th was seated on the driver side in the minicar. The MPV did not have a bumper cross beam, and the engine was not located in the front of the vehicle. In the test, the structural interaction was not good. However, the left front rail of the MPV was stopped by the engine of the minicar. One of the driver seat attachment bolts (rear left-hand) on the floor fractured in the minicar, and the driver dummy moved forward. As a result, the chest acceleration was 599 m/s^2, the chest deflection was 37 mm, and the femur force was 2.3 kN. The HIC was small (298).

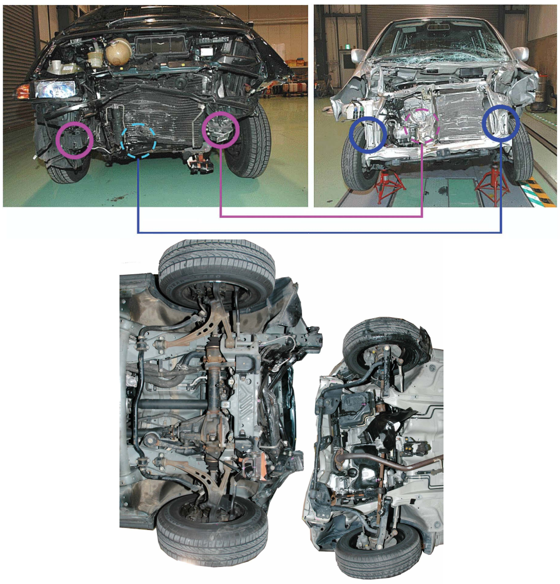


Figure 21. Structural interaction of minicar-to-MPV crash test (Test 3)

In the three car-to-car tests of the minicars, the structural interaction was determined to be acceptable because the engine of the minicar interacted with the structure of the other car, even though the minicar either has no bumper cross beam or has a weak bumper cross beam. This is not inconsistent with the general agreement that the front rail height matching between cars is a prerequisite, which was confirmed from Tests 2A and 2B. The load path from the engine to the suspension member and the passenger compartment is important for minicars.

DISCUSSION

Accident data show that the injury risk of occupants in minicar in all accidents was comparable to that for other size cars. However, the number of fatal and serious injuries to occupants in minicars is larger than other size of cars in vehicle-to-vehicle collisions. One reason for this high injury risk is due to the high deceleration pulse. Another reason is that the intrusion into the compartment of minicars is large since the length of engine compartment (i.e., available crush space) is limited.

The minicars showed good occupant protection in FWRB and ODB crash tests. The minicars have been highly optimized for severe crash tests for both FWRB (55 km/h) and ODB (64 km/h) tests. Minicars show high deceleration pulses since the size of the engine compartment is limited, and the passenger compartment is designed to remain intact. To reduce injury measures of dummies in these severe crash pulses, the seatbelt limiter force of minicars (5 kN) is designed to be higher than that of larger size cars (4–5 kN). This force level might be too severe for elderly people. From accident analysis, chest injuries constitute the largest number of injuries among the body regions to drivers [1]. The main injury sources to the chest were the steering wheel and seatbelt. Many accidents occur at lower velocities than these crash tests. Moreover, minicars are used in cities and impact velocities are inclined to be low. In order to reduce the number of serious injuries, it is necessary to consider the occupant protection of minicars at lower impact velocities than the impact speed specified for the crash tests conducted in the regulation and NCAP.

In the car-to-car crash tests, minicars showed reasonable structural interaction. Though the minicars do not have multiple load paths, the structural interaction was acceptable since the engine was located forward in the vehicle, interacted with the structures of the opposite car, and worked as a load path. In the evaluation of the structural height as measured from the barrier forces in the FWRB and FWDB tests, it might be necessary to develop a measure for the effect of engine on structural interaction. The passenger compartment was intact and the injury measures of driver dummies were less than the IARVs when the impact severity was less than NCAP (55 km/h), though the delta-V of minicars in the car-to-car crashes is inclined to be high because of the mass ratio of the colliding vehicles.

The trend of sales of minicars and small cars will continue when the user demands and the economical situation is considered. Minicars have a stiff front structure and a strong passenger compartment with optimized restraint system. The minicars will be a good example to ensure the crashworthiness of future hyper-mini electric vehicles.

CONCLUSIONS

For minicars, the size is limited and the vehicle mass is small. The crashworthiness of minicars was investigated from various crash tests.

1. The restraint system of minicars was highly optimized using a seatbelt pretensioner, force limiter, and steering axis collapse for the occupant protection when the vehicle was subjected to a high deceleration as experienced in FWRB tests.
2. In the FWDB tests, the TTFs of minicars were inclined to be later than those in the FWRB tests. Because of this later TTFs, the HIC and chest acceleration of the dummies in the FWDB tests can be higher than those in the FWRB tests even though the vehicle crash pulses in the FWRB tests were more severe for the occupants.
3. The intrusion of the passenger compartment in the ODB tests tends to be large because of the limited size of the minicars. The injury measures of the driver dummies in the ODB tests were less than those in the FWRB tests, except for the tibia index. The tibia index exceeded the IARV when the firewall intrusion was 0.12 m or more.
4. In the car-to-car crash tests of minicars, the structural interaction was found to acceptable due to the engine involvement, and the passenger compartment remained intact. When the impact severity was less than that of an NCAP test, the injury measures of the driver dummies were less than the IARVs.

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REFERENCES

[1] ITARDA, Report of accident investigation and analysis 2011, March 2012 (in Japanese).

[2] Japan, Performance as test procedure of the PDB and ODB tests for the light and heavy cars, Informal Group on Frontal Impact 5th meeting, UNECE, 2009.

[3] Huang, M., *Vehicle Crash Mechanics*, CRC Press, 2009.

[4] Edwards, M., Davis, H., Thompson, A., Hobbs, A., Development of test procedures and performance criteria to improve compatibility in car frontal collisions, Proc. Inst. Mech. Engrs. Vol. 217, Part D, J. Automobile Engineering, 2003.

[5] Yonezawa H., Mizuno, K., Hirasawa T. et al., Summary of activities of the Compatibility Working Group in Japan, Paper Number 09-0203, 21st International Technical Conference on the Enhanced-Safety of Vehicles, Stuttgart, Germany, June, 2009.