Effect of Test Conditions on Child Occupant Responses in CRS

Koji Mizuno 1) Takahiro Ikari 2) Kawahara Hiroshi 3) Masami Kubota 4) Susumu Ohsato 5)

1) Nagoya University
2-3) National Agency for Automotive Safety & Victims' Aid
6-1-25 Koji-machi, Chiyoda-ku, Tokyo 102-0083, Japan
4-5) Japan Automobile Research Institute
2530 Karima, Tsukuba, Ibaraki 305-0822, Japan

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ABSTRACT: A child restraint system (CRS) is installed in various vehicles with different seat, seatbelt routing paths, and seatbelt characteristics. In this research, a series of sled tests were conducted using the ECE R44 seat bench utilizing various CRS models under the same crash pulse specified by JNCAP. During the impact in JNCAP, the cushion of the multi-purpose vehicle seat was soft and the CRS rotated, which led to large forward excursions of the CRS and dummy. A trend was observed that there is a linear relationship of the assessment values between the JNCAP tests and the ECE base tests.

KEY WORDS: (Standardized) Safety, Child protection, Child restraint system (Free) JNCAP, ECE R44, Sled test [C1]

1. Introduction

There is a substantial body of research published from accident analyses and experiments which shows that a child restraint system (CRS) is useful in preventing injuries to child occupants. The injury risks to a child occupant in the CRS could be affected by the CRS types as well as the seat characteristics and seatbelt used to install the CRS. Several researchers investigated the relation between the CRS type and the injury risk to the child (1,2). Although CRSs are installed in a wide variety of vehicles with various seats and seatbelts in the real-world usage, there is limited research which investigates the influence of the vehicle seat, the seatbelt path geometry, and the seatbelt characteristics on the responses of the child seated in the CRS. Bell and Burleigh (3) compared the injury measures of the TNO P3/4 dummy in the ECE R44 and FMVSS 214 dynamic test environments. The CRS was installed with a 3-point seatbelt with the seat in the ECE R44 test condition, and it was installed with a 2-point in the FMVSS 214 test condition. The head excursion of the child dummy was larger for the FMVSS 214 test than that for the ECE R44 test because of differences resulting from CRS installation with a seatbelt. The dummy accelerations were comparable, and the authors concluded that loading on the dummy in both tests was equivalent.

The CRS assessment has been conducted in Japan New Car Assessment Program (JNCAP) since 2001 (4,5). The CRS assessment of JNCAP consists of a dynamic test and a usage rating. In the dynamic test, the body of a multi-purpose vehicle (MPV), a Toyota Estima (manufactured in 2000, eight-passengers), is fixed on the sled test device. The CRS is installed on the 2nd row seat behind the driver’s seat. This 2nd row seat was equipped with a three-point seatbelt with a CRS anchoring function (automatic locking retractor function). The retractor and D-ring of the shoulder belt and the anchorage of the outer lap belt are mounted on the B-pillar, and the inner buckle is mounted on the movable seat. The elongation of the seatbelt is 15% at tension of 10 kN (cf. it is specified to be 8 ± 2% for the seatbelt in ECE R44 regulation test). The vehicle seat and the seatbelt used to install the CRS were replaced with new parts before each test. The velocity change of the sled in JNCAP test is 55 km/h which is higher than that in the ECE R44 regulation (50 km/h) by 10%. The sled acceleration curve was adjusted to satisfy the corridor of acceleration-time history provided in ECE R44. A representative acceleration curve was established to secure test reproducibility.

In JNCAP, the CRABI six-month-old (6MO) dummy is used for the bed-type CRS tests because the infant (until 6 months old) can use the bed-type CRS according to the CRS manufacturer. The TNO P3/4 (9 month) dummy is used in the tests of the rear facing (RF) infant CRSs, and the Hybrid-III three-year-old (3YO) dummy is used for the tests on the forward facing (FF) toddler CRSs. The assessment criteria and injury assessment reference values (IARVs) were established in JNCAP for each of the three CRS categories (4,5).

In the regulation, the CRS is tested in accordance with the ECE R44. In this research, to understand the difference in the child occupant kinematic behavior between the JNCAP test condition (MPV seat and seatbelt) and the ECE R44 test condition, the child occupant responses in the car-bed CRS, the RF CRS and the FF CRS under the ECE R44 environment were analyzed, and the results were compared with those obtained in JNCAP. Note that in this ECE base test series, the velocity change (55 km/h) and the dummies (CRABI 6MO, TNO P3/4 and Hybrid III 3YO) were different from those prescribed in the ECE R44 regulation. The results from this research also will be useful for understanding the response of a child occupant seated in a CRS installed in vehicles with various seats and seatbelt geometries.
2. Method

In this study, the tests were conducted in the same condition specified by JNCAP except that the CRS is tested on an ECE R44 test bench. The same acceleration pulse (velocity change 55 km/h) as the JNCAP was provided to the sled (Fig. 1). Fig. 2 shows the FF CRS installed in the 2nd row seat of MPV (JNCAP) and in the ECE R44 test bench. Because of the positions of the D-ring of the shoulder belt and the outer lap belt anchor at the B-pillar bottom, the path of the vehicle seatbelt used to install the CRS was longer in the JNCAP test compared to that in the ECE base test. Table 1 presents the test matrix. Nine CRS models were used. Three (the Aprica bed grande W thermo 750, Bettino STD, and Eurofix) are a convertible type CRS which can be changed to a bed-type, RF, or FF CRS. Four (the Takata04-facil, Leaman Eurobegin, Combi Separate, and Carmate Sukusuku turn) are a convertible type 5-point harness CRS that can be used as a RF or a FF CRS. One, the Maxi-cosi Cabriofix, is an infant RF CRS with 3-point harness.

Among the assessment criteria in JNCAP CRS tests, physical parameters were examined. For the bed-type CRS, the CRS shell inclination angle, the head excursion and the chest acceleration (3 ms) of the CRABI 6MO were examined. In the RF CRS, the CRS seatback inclination angle, and the chest resultant acceleration (3 ms) of the TNO P3/4 dummy were examined. In the FF CRS, the head excursion, the head resultant acceleration (3 ms), and the chest resultant acceleration (3 ms) of the Hybrid III 3YO were compared. In this study, all the data of the dummy were measured with respect to the dummy’s local coordinate system, and they were sampled and filtered in accordance to SAE J211 recommended practice.

![Fig. 1](image1.png) Acceleration-time history of sled (velocity change is 55 km/h).

![Fig. 2](image2.png) Installation of FF CRS in the MPV of JNCAP (left) and ECE bench tests (right).

3. Results

3.1. Bed-type CRS

The responses of the CRABI 6MO dummy laid in the bed-type CRS were compared in the JNCAP test and in the ECE base test. Fig. 3 shows the kinematic behavior of the CRABI 6MO dummy laid in the Aprica Eurofix CRS. During the impact, the CRABI 6MO dummy made contact with the side of the CRS shell, and this kinematic behavior was similar between that in the JNCAP test and that in the ECE base test. The chest acceleration of the CRABI 6MO dummy is shown in Fig. 4. The acceleration of the dummy’s lateral direction (y) is largest. There are two large peaks in the chest acceleration. The chest acceleration has a first peak (68 ms in JNCAP and 64 ms in ECE base test) when the forward movement of the bottom of the CRS support leg stopped on the floor and the axial force of the support leg was applied on the CRS. The chest acceleration decreased when the bottom of the support leg slid on the floor again. Then, the support leg stopped again and the large seatbelt force was applied on the side of the CRS shell, which led to the second peak (79 ms in JNCAP and 83 ms in ECE base test) in the chest acceleration. Accordingly, the chest acceleration was affected by the forces from the support leg and the seatbelt. The head excursion was larger in the JNCAP test than that in the ECE base test probably because the seatbelt path was longer which resulted in increased elongation of the seatbelt in the JNCAP test condition than that observed in the ECE base test.

Fig. 5 plots the comparison of injury measures of the CRABI 6MO dummy in the JNCAP and the ECE base tests. Head excursion in all tests was less than the IARV of JNCAP (600 mm). In contrast, the chest resultant acceleration (3 ms) in all tests exceeded the IARV (539 m/s²). There is a linear relation of head excursion between both tests, with the head excursion observed to be larger in the JNCAP tests than that in the corresponding ECE base tests. According to the linear approximation, the level of the head excursion (600 mm) in JNCAP corresponds to 508 mm in the ECE base tests. On the other hand, there was no observed

![Table 1](image3.png) Test matrix.

**Table 1 Test matrix**

| CRS type | CRS Model          | Infant | Toddler |
|----------|--------------------|--------|---------|
|          |                    | CRABI 6MO | TNO P3/4 | Hybrid III 3YO |
| Support leg | Bed-type | RF CRS | FF CRS |
| Convertible (bed-type, RF or FF) | Aprica Bed grande W thermo 750 | ✓ | ✓ | ✓ |
| Convertible (RF or FF) | Aprica Bettino STD | ✓ | ✓ |
| Convertible (RF or FF) | Aprica Eurofix | ✓ | ✓ |
| Convertible (bed-type, RF or FF) | Takata04-facil | ✓ | ✓ |
| Convertible (RF or FF) | Leaman Eurobegin | ✓ | ✓ |
| Convertible (RF or FF) | Combi Separate | ✓ | ✓ |
| Convertible (RF or FF) | Carmate Sukusuku turn | ✓ | ✓ |
| Infant (RF) | Maxi-cosi Cabriofix | ✓ |
| Impact shield | Recaro Start R1 | ✓ |
relationship in chest acceleration between the JNCAP and ECE base tests. This is because the chest acceleration was affected by the force from the support leg, which in turn during the impact was affected by the contact interaction force between the support leg bottom and the floor.

Fig. 3 CRABI 6MO dummy behavior in bed type CRS.

(a) JNCAP (80 ms)  (b) ECE (80 ms)

Fig. 4 Chest acceleration of CRABI 6MO in JNCAP and ECE R44 base test.

(a) JNCAP  (b) ECE

Fig. 5 Comparison of injury measures of CRABI 6MO laid in car-bed CRS in JNCAP and ECE R44 base test.

3.2. RF CRS

The responses of TNO P3/4 dummy seated in the RF CRS were compared for the JNCAP and the ECE base tests. In all tests, the dummy head was contained within the CRS shell. Fig. 6 shows the kinematic behavior of the dummy in Takata04-facil RF CRS when the inclination angle of the CRS seatback was maximal. Because the path of the seatbelt used to install the CRS in the vehicle went through the bottom of the CRS, a large CRS downward rotation occurred during the impact. Fig. 7 shows the chest acceleration of the TNO P3/4 dummy. In the RF CRS, the chest acceleration in anterior-posterior (x) and upward (z) directions increased together, and according to the CRS rotation, the chest acceleration changed from z direction to x direction. In JNCAP, because the cushion of the seat is soft but does not bottom out in the JNCAP test condition, the chest acceleration in the z direction was not so high. On the other hand, in the ECE base test, the ECE seat cushion bottomed out, and the chest acceleration had a peak at 95 ms.

For the Leaman Eurobegin RF CRS, the lap belt and shoulder belt were routed through the CRS base and CRS seatback, respectively. Fig. 8 shows the kinematic behavior of the dummy and the CRS at the time of maximum chest acceleration. The shoulder belt, which applied the force on the CRS seatback, reduced the longitudinal displacement and downward rotation of the CRS. Fig. 9 shows the chest acceleration of the dummy. In the ECE base test, the chest acceleration increased earlier compared to the JNCAP test, and the dummy chest acceleration was low.

(a) JNCAP (96 ms)  (b) ECE (86 ms)

Fig. 6 Kinematic behavior of TNO P3/4 dummy in RF CRS (Takata04-facil).

(a) JNCAP  (b) ECE

Fig. 7 Chest acceleration-time history of TNO P3/4 dummy in RF CRS (Takata04-facil).

(a) JNCAP (74 ms)  (b) ECE (76 ms)

Fig. 8 Kinematic behavior of TNO P3/4 dummy in RF CRS (Leaman Eurobegin).

(a) JNCAP  (b) ECE

Fig. 9 Chest acceleration-time history of TNO P3/4 dummy in RF CRS (Leaman Eurobegin).
As a result, the head excursion was small and comparable. The head flexion angle was small in this CRS. Fastened this CRS tightly, the CRS rotation and the dummy then CRS rotated forward. In JNCAP, as the shoulder belt because of the initial tensile force exerted by the shoulder belt, CRS. In the ECE base test, the CRS rotated rearward until 60 ms system) to apply tension to the shoulder belt used to install the Takata04-facil FF CRS. This CRS has a device (pre-loader system) to apply tension to the shoulder belt used to install the CRS. In the ECE base test, the CRS rotated rearward until 60 ms because of the initial tensile force exerted by the shoulder belt, then CRS rotated forward. In JNCAP, as the shoulder belt fastened this CRS tightly, the CRS rotation and the dummy rotation were small. The head flexion angle was small in this CRS. As a result, the head excursion was small and comparable between the two tests (497 mm in JNCAP and 494 mm in ECE base test). Fig. 12 shows the chest acceleration of the Hybrid III 3YO seated in the Takata04-facil. The start time of the restraint loading was similar between the two tests, and the chest peak accelerations were comparable between the two tests.

Fig. 13 shows the kinematic behavior of the Hybrid III 3YO dummy seated in a Leaman Eurobegin FF CRS in the JNCAP test and ECE base test, respectively. In the JNCAP test, the CRS rotation was large due to the soft cushion of the MPV seat and long path of the shoulder belt. As a result, the head excursion in JNCAP (582 mm) was larger than that in ECE seat base test (519 mm). Fig. 14 shows the chest acceleration of the Hybrid III 3YO. The restraint of the child dummy started earlier in the ECE base test, which could have led to the smaller chest acceleration of the Hybrid III 3YO dummy. The chest acceleration in vertical direction (z) was larger in the ECE base test since a larger compression force was applied from the seat cushion.

Fig. 15 shows the kinematic behavior of the Hybrid III 3YO dummy seated in a Carmate Sukusukuturn FF CRS (which has a support leg). During the impact, the CRS rotated forward around the support leg bottom that functioned as a fulcrum point. Since the shoulder belt was routed through the CRS base, the CRS rotation was large. At this time during the response, the force was applied to the CRS in the upward direction from the support leg, and as a result the dummy moved upward. This phenomenon was more predominant for the ECE base test. The dummy head rotated in the same manner as the CRS rotation, and the head acceleration was large (749.7 m/s²). Fig. 16 shows the chest acceleration of the dummy. The chest acceleration has a high peak in the upward (z) direction and the chest resultant acceleration was affected by this peak. The timing of the initial interaction of the support leg bottom against the floor was different between the two tests, and the dummy injury measures were affected by the axial force exerted by the support leg on the CRS.

![Fig. 10: Comparison of CRS seatback inclination angle and chest acceleration in ECE and JNCAP tests](image)

**Fig. 11: Comparison of injury measures of CRABI 6MO seated in RF CRS in JNCAP and ECE R44 base test**

**3.3. FF CRS**

The responses of Hybrid III 3YO dummy seated in the FF CRS were compared for the JNCAP and ECE base tests. Fig. 11 shows kinematic behavior of the Hybrid III 3YO seated in Takata04-facil FF CRS. This CRS has a device (pre-loader system) to apply tension to the shoulder belt used to install the CRS. In the ECE base test, the CRS rotated rearward until 60 ms because of the initial tensile force exerted by the shoulder belt, then CRS rotated forward. In JNCAP, as the shoulder belt fastened this CRS tightly, the CRS rotation and the dummy rotation were small. The head flexion angle was small in this CRS. As a result, the head excursion was small and comparable between the two tests (497 mm in JNCAP and 494 mm in ECE base test). Fig. 12 shows the chest acceleration of the Hybrid III 3YO seated in the Takata04-facil. The start time of the restraint loading was similar between the two tests, and the chest peak accelerations were comparable between the two tests.

![Fig. 12: Chest acceleration-time history of Hybrid III 3YO dummy in FF CRS (Takata04-facil)](image)
and thorax spine. In both tests, the sternum touched the thorax spine at the 1st rib level, which indicated that the rib cage bottomed out in this location.

Injury measures (head excursion, head acceleration and the chest acceleration) in the Hybrid III 3YO dummy in FF CRS were compared in JNCAP tests and ECE base tests (Fig. 19). For the head excursion, in the JNCAP tests all CRS models except Takata04-facil were over the IARV of JNCAP (550 mm), and in the ECE base tests three CRS models (Combi Separate, Carmate Sukusuku-turn and Recaro Start R1) exceeded the 550 mm level. For the head acceleration (3 ms), three CRSs (Aprica grande W 750, Leaman Eurobegin and Combi Separate) exceeded 785 m/s² in the JNCAP tests, and all CRS models were less than this level in the ECE base test. For the chest acceleration (3 ms), the Aprica grande W 750 in the ECE base test exceeded the IARV (588 m/s²).

As shown in Fig. 19, the head excursion and the head acceleration of the dummy tended to be larger in the JNCAP tests. In the JNCAP test, as a result of the longer seat belt routing path and the soft seat cushion of the MPV, the dummy head rotated, which could lead to a larger head excursion compared to the ECE base test. There is a linear relationship of the head excursions between the two test types. Using the linear regression line, it is seen that the reference value of 550 mm and 700 mm in JNCAP corresponds to 524.5 mm and 603.1 mm in the ECE base test, respectively. There is also a trend of a linear relationship of the head acceleration between the two test types. According to this approximation, the IARV of 784.5 m/s² in JNCAP corresponds to 650 m/s² in ECE base tests. The data of the Carmate Sukusuku-turn were not used to determine the linear regression equation of the head acceleration because the support leg had a large effect on the head vertical acceleration in this CRS. The shell of the Takata04-facil CRS rotated rearward in the ECE base test, which likely caused a smaller head acceleration than expected by the linear regression line. As shown in Fig. 19(e), the slope of the
approximation line of the chest acceleration between the two tests is 1.07, and it is probable that the severity of chest loading was comparable between the JNCAP test and the ECE base test environment. Note that the data of the Aprica Grande W750 and Carmate Sukusuk-turn were not used to determine the approximation equation of the chest acceleration since they had a support leg which vertical loading had a significant effect on the dummy chest vertical acceleration (z).

However, the relation presented in Table 2 could not be applied when the support leg of the CRS or the bottoming-out of the ECE seat cushion affected the injury measures of the dummy. The support leg is effective for preventing the CRS forward movement and rotation and thereby reducing the head excursion of the child occupant. After the sled started to accelerate, the bottom of the support leg slid forward on the floor. When this movement came to a stop, an axial force in the support leg was transmitted to the CRS, which affected the chest acceleration of the dummy. The CRS could rotate around the support leg bottom, which led to higher acceleration of the head because of the dummy rotation. Accordingly, the interaction between the support leg bottom and the floor has a large effect on the dummy kinematic behavior and the dummy accelerations. Moreover, during installation the support leg length is adjusted according to the seat height. Consequently, the injury measures for a dummy seated in a CRS that has a support leg could be dependent on the test bench setup and floor in which the CRS is tested. In the test series of present study, for the CRS with large rotation, the bottoming-out occurred in the ECE seat cushion. This bottoming-out could affect the chest acceleration of the dummy. The bottoming-out of the ECE seat cushion could be more severe in the test series of this research (velocity change 55 km/h) than the less severe test conditions of the ECE R44 regulatory tests (50 km/h).

![Fig. 19 Comparison of injury measures of Hybrid III 3YO seated in FF CRS in JNCAP and ECE R44 base test.](image)

| CRS type | Injury measures | JNCAP limit | Equivalent value ECE R44 | Approximation equation |
|----------|-----------------|-------------|-------------------------|-----------------------|
| Bed-type | Head excursion  | 600 mm      | 508 mm                  | $Y = 0.899x - 31.4$   |
| CRAB 6MO | Chest acceleration | 539 m/s² | NA          | NA                  |
| Rear CRAB 6MO | Seat back inclination angle | 60° | 55.5° | $Y = 0.828x + 5.8$ |
| Chamber | Chest acceleration | 539 m/s² | 447 m/s² | $Y = 0.709x + 64.4$ |
| Foward facing | Head excursion | 70° | 63.7° | |
| Hybrid III 3YO | Chest acceleration | 550 mm | 524.5 mm | $Y = 0.524x + 2363$ |
| | Head acceleration | 784.5 m/s² | 649.8 m/s² | $Y = 0.798x + 23.8$ |
| | Chest acceleration | 588.4 m/s² | 605.8 m/s² | $Y = 1.07x - 25.6$ |

4. Discussion

The seat characteristics and the seatbelt routing path utilized to install the CRS are different between the JNCAP tests and ECE R44 tests. In this research, a series of CRS tests were carried out using ECE R44 test bench at a velocity change of 55 km/h, and the results were compared with JNCAP. In the JNCAP tests, the soft seat cushion and the higher degree of seatbelt elongation resulting from the longer seatbelt routing path utilized to install the CRS led to larger forward excursions and downward rotations of the CRS and the dummy. On the other hand, in the ECE base test, the seatbelt routing path utilized to install the CRS is shorter and the seat cushion could bottom out. In general, the IARVs of the bed-type, RF, and FF CRSs tended to be larger in the JNCAP tests than those in the ECE base tests. A trend was observed that there is a linear relationship of the IARVs between the JNCAP tests and the ECE base tests. Table 2 presents the IARVs of JNCAP test and their equivalent values in the ECE base test at 55 km/h. It is likely that in general the CRS model performance can be assessed though they are installed in a different environment of the seat and the seatbelt.
which may increase the chest acceleration of the dummy. These inverse factors could contribute to the comparable chest acceleration of the dummy seated in FF CRS in the two tests.

For the impact shield CRS, the responses of the Hybrid III 3YO dummy were comparable in the JNCAP test and in the ECE base test though the injury measures were more severe for the JNCAP test. The tested FF impact shield CRS has a simple system in which the seatbelt is routed through the shield and there are no harnesses in the CRS shell. It is likely that the dummy responses in the FF impact shield CRS were affected mainly by the seatbelt, and the effect of the seat used to install the CRS was small.

![Seatbelt buckle geometry and CRS.](image)

(a) JNCAP  
(b) ECE R44

Fig. 20 Seatbelt buckle geometry and CRS.

5. Conclusion

Three models of Bed type CRSs, six models of RF CRSs and six models of FF CRSs were tested in the ECE R44 seat bench with a velocity change of 55 km/h. The dummy measurements were compared with that of CRS sled test in JNCAP (2nd row seat of MPV). The results are summarized for the car-bed, RF and FF CRS as follows:

1. In the car-bed CRSs, the head excursions of the CRABI 6MO dummy in the JNCAP tests was larger than those in the ECE base tests, and there was a linear correlation of the head excursions between the two test types. On the other hand, there was no observed correlation in chest acceleration between the two test types since the support leg had a large effect on the chest acceleration.

2. In the RF CRSs, the CRS seatback downward angles and the chest accelerations of the TNO P3/4 dummy were larger for the JNCAP tests compared to those in the ECE base tests. There is a linear correlation in these parameters between the two test types. When the ECE cushion bottomed out as a result of the CRS rotation, the chest acceleration was large.

3. In the FF CRSs during impact, according to the level of rotation of the soft seat in the JNCAP test, the CRS rotated and had a downward movement. The head excursions of the Hybrid III 3YO dummy was larger in the JNCAP tests than those in the ECE seats, and there was a linear relation of the head excursions between the two test types. Although the chest accelerations were comparable between the two test types, the bottoming-out of the ECE seat cushion or the support leg interaction could have an effect on the chest acceleration of the dummy.

References

(1) Melvin W, Weber, K: Abdominal Intrusion Sensor for Evaluating Child Restraint Systems, SAE Congress, SAE Paper 860370 (1986).
(2) Langwieder K, Hummel T, Finkbeiner F., Injury Risks of Children in Cars Depending on the Type of Restraint. Child Occupant Protection in Motor Vehicle Crashes, Wiley (1999).
(3) Bell R, Burleigh D.: An Empirical Comparison of the FMVSS 213 and ECE 44.03 Standards for Child Restraints, SAE Congress, SAE Paper 973312 (1997).
(4) Ono Y, Hosono T, Takatori O.: Child Restraint System Assessment Program in Japan, 18th International Technical Conference on the Enhanced Safety of Vehicles, Paper number 241 (2003).
(5) Ono Y, Komiyama Y, Takatori O.: Method of Evaluating Abdominal Injury in Japan's Child-Restraint-System Assessment Program, 19th International Technical Conference on the Enhanced Safety of Vehicles, Paper number 05-0292 (2005).
(6) Hu J, Mizuno K.: The Kinematic Behaviour and Responses of Hybrid III 3YO Dummy and Child Human FE Model in ISOFIX CRS in Frontal Impact. International Journal of Crashworthiness, Vol. 14, No. 4, pp. 391-404 (2009).