

**Artigo Original**

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**Static analysis of harness fit in forward-facing child restraints**

*Análise estática do posicionamento do sistema de cinco pontos em dispositivos de retenção infantil*

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**Abstract**

The present study examines several important contributors to appropriate child restraint systems (CRS), including harness routing (chest and lap straps) and the location of important protective components. Three forward-facing CRS equipped with five-point harnesses were evaluated in a laboratory vehicle mockup using the Hybrid-III three-year-old crash dummy. CRS elements and landmarks on the dummy were recorded using a three-dimensional coordinate digitizer (FaroArm). It was analyzed some important CRS components to the security of children in an impact. Results showed that harness routes and the lateral head frame varied widely among the CRS. Variation in harness slot position produced differences in fit at the shoulders and chest. Lap straps on one CRS routed the straps onto the dummy's abdomen rather than the preferred pelvis position. The CRS lateral supports for head also varied relative to the dummy head center of gravity indicating that, in some cases, the head may not be laterally protected and move through a wide range in a car lateral impact which might cause injury. The results of this study suggest that the design of CRS still fail to fit all anatomical differences in the age range it is designed for.

**Keywords:** Car seat, Misuse, Children safety, Components, Injury.

**Resumo**

O presente estudo tem a finalidade de avaliar o sistema de proteção dos dispositivos de retenção infantil, tais como a passagem do cinto de cinco pontos, referentes às tiras do torso e abdominais, e também avaliar a localização de componentes de proteção. Três modelos de dispositivos foram analisados em laboratório simulador no banco traseiro de veículo usando um dummy de três anos da família Hybrid III. A coleta de dados foi feita por meio de marcas predeterminadas no dummy e nos dispositivos e registradas tridimensionalmente por um equipamento digitalizador de pontos em 3D (FaroArm). Para isso, o dummy foi instalado nos assentos após sua fixação no carro seguindo os padrões da norma norte-americana nº 213, da Federal Motor Vehicle Safety Standard – FMVSS “Child Restraint Systems” (NHTSA, 2005). Os resultados mostraram uma grande variação no posicionamento dos componentes de proteção entre os modelos analisados. O cinto do torso apresentou diferenças em sua passagem no tórax superior conforme a altura de regulagem. A posição do cinto abdominal também variou entre os modelos, sendo observada a passagem do mesmo na região do abdômen ao invés de locais mais rígidos, como os ossos da pélvis. Além disso, a localização do componente lateral de proteção da cabeça sofreu grande variação em relação ao centro de gravidade de cabeça do dummy, indicando que, em alguns casos, a cabeça da criança pode não ser protegida lateralmente por se deslocar amplamente no caso de impacto lateral do carro, o que provocaria lesão. Os resultados deste trabalho sugerem que o design de assentos infantis ainda apresenta falhas quanto ao posicionamento dos componentes de proteção em relação às características anatômicas da criança, considerando a ampla faixa etária para que são fabricados.

**Palavras-chave:** Dispositivo, Segurança, Infantil, Mau uso, Lesões.

## Introduction

The number of children being transported in vehicles is increasing continuously. However, many children are reported to be poorly restrained or misusing the safety devices (Decina and Lococo, 2005). According to Brown *et al.* (2006) the level of injury in children using child restraint systems (CRS) differs significantly among optimally restrained and suboptimally restrained children.

Common types and causes of CRS misuse have been identified in previous studies (Brown *et al.*, 2009; Lee *et al.*, 2008; Snowdon *et al.*, 2008). The U.S. National Highway Traffic Safety Administration (NHTSA, 1996) listed improper orientation of CRS and poor harness fit as two of the most common errors. According to Decina and Lococo (2005) improper positioning of harness straps relative to the child and improper routing of the harness through the CRS were the most common misuse modes observed for children in forward-facing harness restraints.

Because of restraint misuse and the outcome injury patterns in crashes, the study of the fit of children in CRS, and CRS in vehicles, has become an important issue to be investigated in the transportation field. Huang and Reed (2006) studied the anthropometric data of older children in relation to vehicle's dimensions. Torso and lap belt fit has also been studied statically among children using belt-positioning boosters (Reed *et al.*, 2009). However, the harness fit for younger children has not been addressed with the same details yet. In a survey regarding to the likelihood of sustaining serious injury in car accidents related to occupant's age, Lardelli-Claret *et al.* (2006) showed that children under 3 years old are among the age range that most sustain serious injuries in vehicle transportation. Bilston and Sagar (2007) evaluated the back heights and harness slots height of 17 CRS designs relative to anthropometric data of children up to five years old. The findings suggested that CRS dimensions fitted properly all range of children designated for them when considering seat back height, restraint width and slot locations.

Static tests differ from dynamic tests in terms of car seats evaluation. While dynamic tests evaluate car seats performance regarding to thoracic and head accelerations and excursions, the static test evaluates the interaction between dummy and car seat by pointing the belt fit that is preferred to prevent injuries.

For this reason, the present study aimed to analyze the harness route in three different models of

forward-facing CRS and evaluate elements location relative to the dimensions of an Anthropomorphic Testing Device (ATD, i.e., crash dummy), representing a three-year-old child in a static test.

## Materials and Methods

### Child restraints

Three different models of forward-facing CRS (CRS1, CRS2 and CRS3) were tested in a laboratory mockup. The CRS are intended for the Brazilian market and all three CRS are at least designed for children in Group I, which includes children from 1 to 3 year old. CRS1 is also recommended for the Groups II and III (3-7.5 years old) and CRS2 is designed for Group II as well (2.5-5 years old). All CRS are equipped with a five-point harness system and two of them were padded over the chest straps (CRS2 and CRS3).

### Testing set up

Tests were executed in a Laboratory for static evaluation in the Transportation Research Institute of the University of Michigan (UMTRI).

Child restraints systems were installed according to each manufacturer's instructions in the right outboard position on a laboratory mockup of a 2002 Pontiac Grand rear seat (Figure 1). The mockup had a three-point belt system with a sliding latch plate. The vehicle's rear seat angles were fixed at 23° for back (torso) angle (SAE A40) and 14.5° for cushion angle (SAE A27). The cushion length was set to 400 mm.

Data were collected with the Hybrid-III three-year-old ATD, which weighs 16 kg and has a 55-cm sitting height. The ATD was installed according to the procedures in the U.S. Federal Motor Vehicle



**Figure 1.** Mockup used for CRS installation. The FaroArm equipment is indicated by the white arrow.

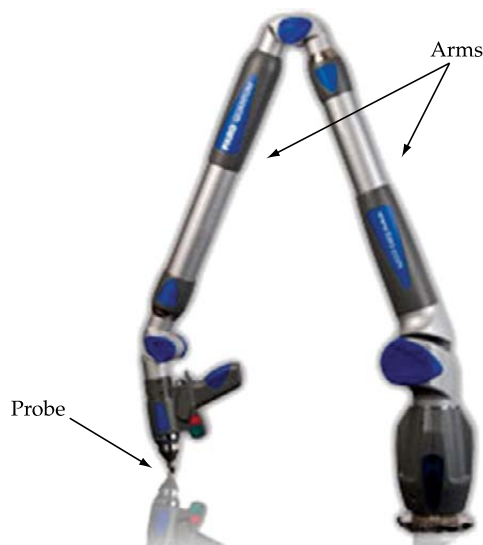
Safety Standard (FMVSS) 213 for static tests. Hence, after placing the ATD in the car seat, a force of 178 N (18.14 kg) was applied first at the ATD lower abdomen and then at the thorax using a flat square surface gage with a 25 cm<sup>2</sup> area.

The harness was routed through the upper slots in all three CRS.

### Digitized data

To analyze the fit characteristics of the ATD in each CRS, the three-dimensional locations of selected landmarks on the ATD, CRS and vehicle seat were recorded using a portable coordinate digitizer (FaroArm, model B08 Bronze) shown in Figure 2. The FaroArm is a coordinate digitizer with high flexibility enabled by its several joints reaching any point desired to the measurement. There is a probe at the tip that computes the landmarks position in 3D at the software with high accuracy. The applications of the FaroArm are several including inversion engineering by digitizing real dimensions into virtual documentation, pre and post deformation analysis in the automobile or aerospace field.

In this study, the FaroArm was used to digitize harness routes and CRS components locations in relation to dummy's landmarks. Before the landmarks recordings, the equipment was calibrated using in a laboratory coordinate system with X positive rearward, Y positive to the right, and Z positive upward relative to the seating position. To record data, the experimenter placed the tip of FaroArm on



**Figure 2.** The FaroArm equipment showing the probe at the tip and arms.

the located landmarks and pressed a button. The 3D landmark localization was immediately originated in a spread sheet software. Single point measurements errors were indicated to be  $\pm 0.304$  mm.

Table 1 lists dummy's digitized points while CRS and vehicle seat landmarks are listed in Table 2.

Figure 3 shows the digitizing data on the 3 year old ATD while seated in the CRS.

**Table 1.** ATD Landmarks.

Regions	Landmarks
Head	Head center of gravity (HCG)
Thorax	Top of chest in the midst point between shoulder joints
Abdomen	Abdomen left and right lateral marks
Upper extremities	Shoulder joint, elbow joint, wrist joint
Lower extremities	Hip joint, knee joint, ankle joint, ball of foot

**Table 2.** CRS and Vehicle Seat Landmarks.

	CRS	Vehicle Seat
	Slots – inboard and outboard edges	D-ring – 3 reference points
Harness system	Chest straps where it touched dummy's shoulder	Seat belt contact on car seat and vehicle seat
	Pelvic straps where it touched dummy's abdomen	
	Lateral component for head protection	Buckle – 3 reference points



**Figure 3.** Digitizing thoracic point in the 3YO ATD.

## Results

The overall fit of the 3 year old dummy on the forward-facing car seats is shown in Figure 4. In this study, the CRS fit was analyzed in terms of chest straps and lap straps routes on ATD and according to the position of the ATD head center of gravity (HCG) relative to the components of the CRS intended for head protection in lateral impacts.

Regarding to harness fit, chest straps fit differed according to slot's positioning. In this study, all slots were intended to be used above dummy shoulder's height (Weber, 2000). Therefore, the most upper slots were used in all car seats. Figure 5 shows the two landmarks measured: ATD shoulder joint (yellow dot) and upper slot (red dot) to evaluate chest straps fit.

The vertical distance between these points is shown in Figure 6. The chest strap fit changes according to the distance measured in the vertical direction between shoulder joint and slot, indicating that when the slot is located much higher than dummy's shoulder, it tended to guide chest straps closer to the neck (Figure 5, CRS3). Slots positioned closer to dummy's shoulder guided the straps to route more tightly in the shoulder thus not touching the neck or the head (Figure 4, CRS1 and CRS2). The strap padding on the CRS2 and CRS3 may have contributed to these findings.

Lap strap fit is schematically demonstrated in Figure 7. Analyzing the position of lap straps and lateral abdomen marks digitized from Faro Arm, CRS3 routed the lap straps higher, well up on the

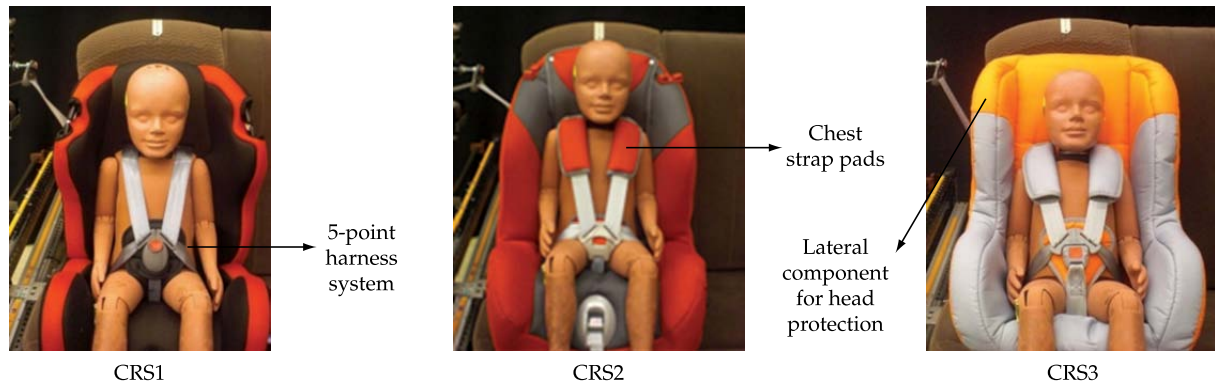


Figure 4. ATD fit on the three different models of CRS.

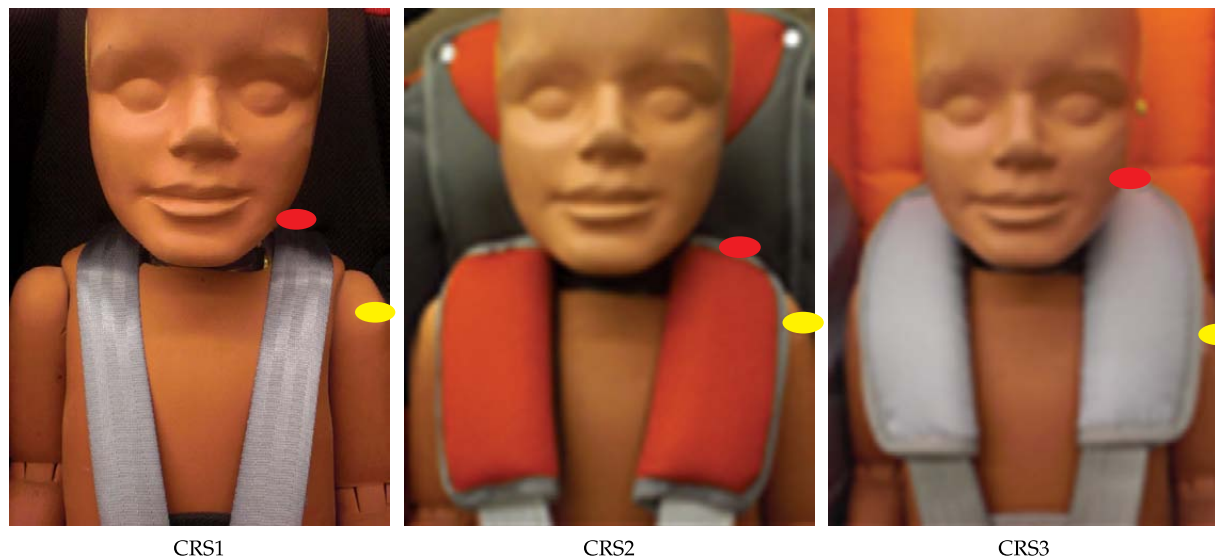
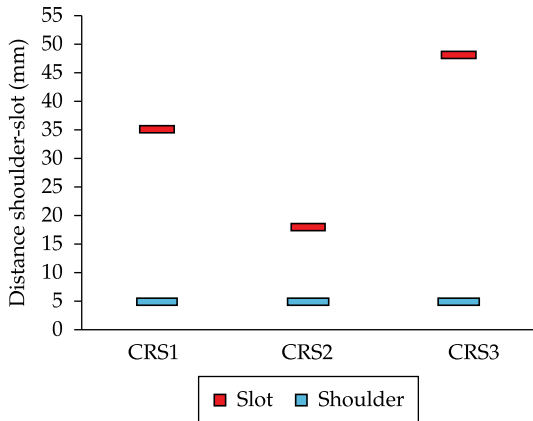
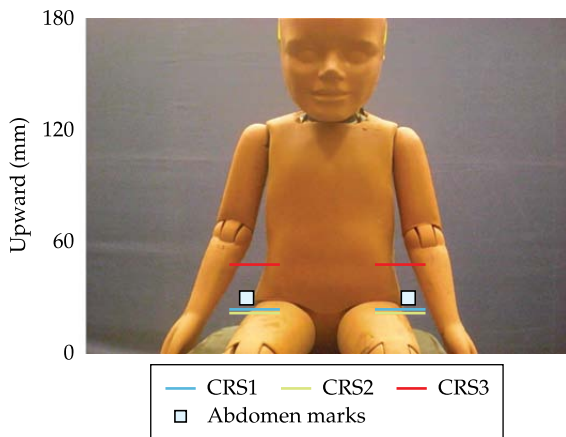


Figure 5. Points measured for the chest straps fit. The red dot represents the slot and the yellow dot represent shoulder's joint.



**Figure 6.** Distance between dummy' shoulder and slots in CRS1, CRS2 and CRS3. Measurements (in mm) are in the upward-downward direction (Z plane).



**Figure 7.** Lap straps fit across CRS illustrated relative to the ATD.

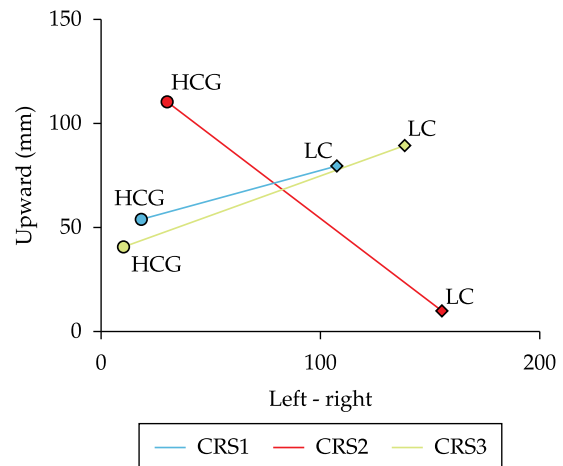
abdomen of the ATD. A lower harness routing that directed restraint loads onto the pelvis, as in CRS1 and CRS2, would be preferred.

The locations of the lateral CRS components designed for side-impact protection were analyzed relative to the ATD HCG (Figure 8). Although all car seats complied with the back-height standard criteria (the HCG is lying below the top of the back), the lateral component protection can be misaligned with the HCG as seen in Figure 8 for CRS2 where the HCG is placed much higher than the lateral component being missed by it.

The HCG can be more protected if covered by the lateral component in the upward direction, as observed in Figure 9 for CRS1 and CRS3 (Figure 9).



**Figure 8.** ATD head center of gravity (arrow).



**Figure 9.** Lateral component (LC) position in relation to the dummy's head center of gravity (HCG). Front view, measurements are in mm. The plot shows only the outboard measurements, i.e. the left side of both dummy and CRS.

### Discussion

The current study evaluated the fit provided by three CRS using the Hybrid-III three-year-old ATD. The results showed that chest strap fit was affected by slot position. Better chest strap fit was observed in slots that are positioned just above shoulder height (Figure 4, CRS1 and CRS2). In these cases, the slot guided chest straps right over the shoulder not touching any other structures, such as neck and basis of head. Ideal, a

slot position just above the child's shoulders should be used. However, the CRS3 upper slot was much higher than ATD shoulder height, guiding chest straps through the basis of head and neck (Figure 4). The number of slots set varied through the car seats. CRS1 had three sets of slots whereas CRS2 and CRS3 had only two sets of slots. The strap padding on CRS2 and CRS3 did not affect the fit measures, but could improve comfort for children, particularly for smaller children who would experience strap positions closer to their necks.

The lap strap fit was analyzed relative to the ATD pelvis and abdomen. A lap strap route that engages the pelvic bones is preferred (Reed *et al.*, 2008). In this study, CRS1 and CRS2 provided better fit in the lap area, routing the straps low, at the thigh abdomen junction. In contrast, the lap straps in CRS3 lay above the pelvis, on the abdomen (Figure 6).

Forward-facing car seats are commonly used for children aged 1 through 4 years. Considering that their sitting height advances along years, lateral components intended for head protection in lateral impact should span an appropriate vertical range. The lateral head protection components of CRS1 and CRS2 extended above the ATD head CG (Figure 8). In contrast, the ATD head CG lay above the lateral head protection components of CRS2, which may represent an increased risk for injury in side impacts (Lai *et al.*, 2009). Most serious injuries to children in side impact are to the head (Ehrlich *et al.*, 2006), so head protection in side impact should be a priority.

## Conclusion

This study shows some mismatches between CRS and ATD dimensions. However, only one ATD size was used, while children vary widely in size and shape. The results highlight the need to consider harness fit and the layout of protective elements of CRS in the design and assessment of CRS. Protection for children in crashes may be improved by close attention to the fit of the CRS and its components.

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