MINIMIZING THE RISK OF LAP/SHOULDER BELTED CHILDREN SUBMARINING THE LAP BELT IN FRONTAL CRASHES

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ABSTRACT

The objective of the study presented by this paper was to determine whether belt-positioing-booster seats incorporate seat bottom design features, identified by previous research, to minimize the risk of submarining. The booster seats were evaluated through inspection and testing. The geometry of the BPB's seat bottom was measured and recorded. The comparative restraining ability of the BPB's seat bottom ramp was tested. The compressibility of the BPB while seated on a vehicle seat was tested. The compressibility of the BPB alone was also tested using the test specified in the Canadian and Australian/New Zealand standards.

The inspection and load testing of various BPBs, as reported in this paper, reveals that BPB seat bottom designs vary significantly. Some BPBs incorporate significant seat ramp geometry and have very little compressibility. Others have no seat ramp at all and have very high compressibility. It is critical that BPB manufacturers understand the importance of anti-submarining seat bottom ramps and low compressibility of the seating surface, and incorporate these features into all BPBs. To ensure this and do so in a manner that is consistently compatible with vehicle seats and seat belts, the authors recommend that NHTSA develop and incorporate requirements into FMVSS 213 specifying the BPB's seating surface geometry and compressibility characteristics, including the seating surface compressibility requirement specified in the Canadian and Australian/New Zealand standards. In lieu of such requirements, the manufacturers of BPBs and automobiles must work together to ensure that the BPB component integrates properly with the seats and seat belt systems at all automobile occupant positions that can be used by a child to ensure that submarining is prevented.

BACKGROUND

After the introduction of seat belts for adults, occupants frequently sustained severe abdominal and lumbar spine injuries during frontal crashes due to the lap belt slipping off the iliac spines of the pelvis and loading into the soft abdominal region.[1,2,3] This kinematic pattern is referred to as "submarining" the lap belt, and the resulting injury is generally referred to as "seat belt syndrome."[4,5] Research has identified several design attributes of the seat belt and vehicle seat that are critical to prevent occupant submarining when using a continuous loop lap/shoulder seat belt. These attributes are:

- A lap belt geometry with an angle greater than 45 degrees from horizontal
- Maximization of the distance of the lap/shoulder belt junction to the centerline of the occupant's body
- Minimization of downward and forward displacement of the pelvis by limiting the compressibility of the seat bottom cushion and incorporating an anti-submarining seat bottom ramp[6,7,8,9,10,11,12,13,14,15,16,17]
- Countering of the force and moment applied to the pelvis by the lap belt that tends to rotate the top of the pelvis rearward by applying a load to the bottom of the pelvis from a structural anti-submarining ramp in the seat bottom.[18,19,20, 21,22,23,24,25,26]

Figure 1 provides an example of a vehicle seat that incorporates an anti-submarining ramp or beam to minimize the potential of submarining.

Figure 1. **2001 Volvo S60 Right Front Seat Bottom Ramp.**

Children, when they outgrow child safety seats with integrated harnesses, are too small to properly fit an adult lap/shoulder belt. Additionally, a child's body is not as compatible with a lap/shoulder belt restraint as the adult body. First, the child's pelvis is not fully developed. The anatomical features of the adult pelvis that engage with the lap belt are the anterior superior iliac spines (ASIS).[27,28] Their shape helps to keep the lap belt engaged with the pelvis. The ASIS of the child's pelvis are not well defined. Therefore, the potential for the lap belt to slip off the pelvis onto the abdomen is much greater. [29,30,31,32] The risk of adult occupants submarining is reduced by their knees and feet often loading against vehicle structure forward of their occupant position during frontal crashes. Because of their shorter legs, such loading will not typically occur with children, which further increases their potential for submarining.

To improve the fit of adult lap/shoulder belts used by children, BPB seats are required.[33,34] The BPB raises the seated shoulder height of the child. This improves the positioning of the shoulder belt, resulting in it being farther from the neck and more centered on the shoulder. It also raises the child's pelvis, thus allowing the lap belt to assume a more vertical orientation, and increases the distance from the lap/shoulder belt junction to the centerline of the child's body. Both of these factors help to maintain the lap belt on the pelvis of the child. The BPB seating surface also has a shorter fore/aft dimension compared to the vehicle seat. This allows the child to sit more comfortably by enabling the knees to bend in a more natural manner than when the child sits directly on the vehicle seat. This decreases the child's tendency to slump in order to allow the knees to bend. Slumping tips the pelvis back, further increasing the potential for the lap belt to slip off the pelvis. After introduction of BPBs in the 1970s,[35] there was not the expected reduction in abdominal injuries in children. Investigators found that the BPB itself typically did not incorporate the countermeasures required by a seating system to prevent submarining of the lap belt. Many of the BPBs' seating surfaces were highly compressible, did not incorporate anti-submarining seat ramps and/or seat belt guides.[36,37,38] In response to the hazard created by highly compressible seating surfaces, Canada and Australia/New Zealand adopted requirements in their standards that limited the compressibility of BPB seating surfaces to 25 and 32 mm (1 and 1¼ inches), respectively, when a 2250 N (~506 lbs) force is applied.[39,40] Researchers also determined that BPBs needed lap belt guide hooks to resist the lap belt moving upward off the pelvis. Because of these realizations and requirements, the majority of BPBs incorporated anti-submarining ramps, low compressibility seat bottom seating surfaces, and lap belt guide hooks. This resulted in a reduction in the frequency of the abdominal and spinal injuries by children restrained by adult lap/shoulder seat belts when using a BPB. [41,42]

There are no requirements in NHTSA's Federal Motor Vehicle Safety Standard (FVMSS) 213 - Child Restraint Systems directly pertaining to the design and performance of BPB with regard to submarining. [43] There is a 915 mm (36 inch) limit on knee excursion limit on all forward-facing child restraint systems when tested in accordance with 48 km/h (30 mph) frontal crash sled test. However, this requirement was incorporated before the introduction of BPBs, with the hope that a child safety seat that allowed submarining would fail the knee excursion requirement. However, with a BPB, the child dummy's knees are typically positioned farther back, because the booster has a thinner, or no, seat back. As a result, the dummy can submarine the lap belt without failing the knee excursion limit. Also, research has found that the current state of the art child dummy is ineffective at revealing a risk of submarining, due to non-biofidelic high stiffness in the lumbar spine. [44]

METHODOLOGY

Four different studies (Studies A, B, C, and D) were conducted to assess the anti-submarining seat bottom ramp and seat bottom compressibility of several different BPBs. The methodology of each study is provided below.

A: BPB Seating Surface Geometry Comparison

The contour of each BPB seating surface was examined and documented using a contour gauge. The angle of the seating surface from horizontal was also measured at 152, 203, 254, and 305 mm (6, 8, 10, and 12 inches) from the rear edge of the booster seat or the booster seat's seat bight, when it incorporated a seat back.

B: BPB Seating Surface Pelvic Restraint Test

The objective of the BPB's Seating Surface Pelvic Restraint Test was to determine the ability of the BPB's seating surface structure to apply a restraining load to the bottom of a child's pelvis. The test methodology, developed by researcher Svensson, [45] was conducted as follows:

1. The upholstery covering the seat bottom of the BPB was removed prior to testing to allow observation of the BPB seat bottom structure during the test. Each BPB was secured to a hydraulic ram fixture. The orientation of the BPB bottom was flat relative to the horizontal travel of the ram. The lower torso/buttocks of a Hybrid III 6-year-old child dummy was attached to the end of the ram. The end

of the ram was positioned on the BPB seating surface where a child would normally sit (Appendix A). The travel of the ram was limited to horizontal displacement only. The loads applied to the lower torso of the dummy were measured by the dummy's triaxial lumbar load cell. Horizontal displacement of the ram was measured by a string potentiometer. Pre-test still photographs of the test article and test set-up were taken.

2. The ram was slowly pulled horizontally toward the front edge of the BPB until it reached the front edge. Load, displacement, and time data were measured concurrently and recorded by a data acquisition system. Each test was video recorded.

3. Post-test photographs were taken of each test article prior to and after removal from the test fixture.

C: BPB/Vehicle Seat Bottom Compressibility Test

The objective of this testing was to determine the capability of BPBs' seat bottom structures to minimize downward displacement of the child's pelvis during a frontal crash.

The test methodology used was a variant to the Svensson methodology.[46] The protocol for the compressibility testing was as follows:

Samples of various Belt-Positioning-Boosters (BPB) were acquired. Each was subjected to seat bottom compression testing. The testing was conducted as follows:

1. The upholstery covering the seat bottom of the BPB was removed prior to testing to allow observation of the BPB's seat bottom structure during the test. The BPB was placed on a vehicle seat bottom and secured to the seat by a lap belt. The fixture oriented the bottom of the vehicle seat bottom to an angle of 25 degrees (front edge up) such that the hydraulic ram applied a forward and downward load to the BPB's seating surface (Appendix B). The loading surface of the ram incorporated the lower torso/buttocks region of a Hybrid III 6-year-old child dummy. The movement of the ram was limited to horizontal. Pre-test still photographs were taken of the test article and test set-up.

2. The load applied was increased during the test as required to maintain the slow forward travel of the ram. The loads applied were measured via the triaxial lumbar load cell within the child dummy's lower torso. Displacement of the ram was measured via a string potentiometer attached to the end of the ram. The data was recorded by a data acquisition system that recorded the load data relative to time and displacement. The test was video recorded.

3. The load maintained slow forward travel of the ram until the dummy's buttocks reached the forward edge of the booster or a vertical or longitudinal force of 4448 N (1000 lbs) to the lumbar load cell was exceeded.

4. Post-test photographs were taken of the test article prior to and after removal from the test fixture.

D: Belt-Positioning-Booster Compressibility Test

This testing was conducted in accordance with Canadian Motor Vehicle Safety Standard (CMVSS) 213, Section 408, which states: "After the application of a preload of 175 N to the booster seat, the booster seat, including any padding or covering, must not deflect more than 25 mm under the application of a vertical force of 2250 N applied anywhere on the upper seating surface of the booster seat through the apparatus described in section 17 of ASTM D3574-08, *Standard Test Methods for Flexible Cellular Materials — Slab, Bonded, and Molded Urethane Foams*, published by ASTM International." ASTM D3574-08 specifies that the indentor that loads the booster seat be a flat circular foot 200 mm +3/-0 mm (8 inches) in diameter.

TEST AND EVALUATION RESULTS

Belt-Positioning-Booster Seating Surface Geometry Comparison

The contours of the seating surfaces of eighteen BPBs were measured and recorded. Plots of the contours are provided in Appendix C. The angles of each BPB's seating surface were measured at multiple locations along the longitudinal centerline and are provided in Appendix D. The complete front edge contour was not always acquired due to the limits of the contour gauge.

The fore/aft depth of the BPBs seat bottom ranged from 289 to 400 mm (11 3/8 to 15 ¾ inches. The maximum angle of the seat bottom surface of the BPBs ranged from 3 to 19 degrees from horizontal. The average maximum seating surface angle was 12.4 degrees. Only one BPB had a maximum a seat surface angle of less than 5 degrees. That BPB had a maximum angle of only 3 degrees 6 inches from its rear edge, and was actual a negative angle of -1 degree at 203 and 254 mm (8 and 10 inches) from its rear edge. Four BPBs had a maximum seating surface angle between 5 and 10 degrees. The remaining thirteen BPBs all had seating surface angles that equaled or exceeded 10 degrees.

Belt-Positioning Booster Seating Surface Pelvic Restraint

The force required to push the dummy pelvis from the normal seating position to the front edge of the BPB without allowing it to move upward was measured. The results are provided in Appendix E. Due to limited test assets, only 15 BPBs were subjected to this test series.

The force application by the hydraulic ram was stopped after either the vertical (z) or longitudinal (x) lumbar loads exceeded 4448 N (1000 lbs), even if the front edge of the BPB had not been reached. Due to both human and hydraulic ram response times, however, the force applied to the booster exceeded that level in several tests. Three BPBs generated a resultant force of less 2224 N (500 lbs) resisting the movement of the pelvis. One of those only generated 173 N (38.9 lbs) of force. Six BPBs generated a resultant force between 2224 and 4448 (500 and 1000 lbs), and six exceeded 4448 N (1000 pounds).

BPB Seat Bottom & Vehicle Seat Compressibility

The force-deflection results acquired during the BPB seat bottom/Vehicle Seat compressibility testing is provided in Appendix F.

At six inches of displacement, the all of BPBs generated a force ranging between 200 lb and 2224 N (500 lbs), except for the Harmony Youth Booster. At 6 inches of displacement, it only generated approximately 150 lbs. and it never exceeded 200 lbs. whereas all of the other BPB exceeded 1200 lbs. The force-deflection characteristics of the various BPBs while, positioned on a vehicle rear seat (2005 Dodge Stratus) varied widely amongst the units tested. When compared at 2224 N (500 lbs) of resultant force the combined deflection of the vehicle seat bottom and BPBs ranged from approximately 165 to 216 mm (6.5 to 8.5 inches), except for one BPB. That BPB did not reach a resultant force of 2224 N (500 lbs), however it did experienced nearly 381 mm (15 inches) of combined deflection.

Canadian/Australian BPB Compressibility Test

The results of the testing conducted in accordance with the Canadian and Australian/New Zealand child restraint standards are provide in Appendix G and H. Prior to this testing, the authors became aware of a unique inflatable BPB called the "Bubble Bum." This BPB was added to the units tested. Those BPBs that exceeded the Canadian 25 mm (1 inch) deflection requirement were tested a second time to confirm the result. Due to a significant difference between the first two tests of the Harmony Youth BPB, three additional tests of that BPB were conducted. All but two BPBs complied with the Canadian 25 mm (1 inch) deflection limit. The two BPBs that failed are shown in Figures 2 and 3, while subjected to the 2250 N (506 lbs) force. One other BPB deflected to the limit. Subsequent to this testing, the authors learned that the Harmony Youth Booster sold in Canada incorporated thicker walls than the U.S. version. Therefore, Canadian Harmony Youth Boosters were subsequently acquired and tested.

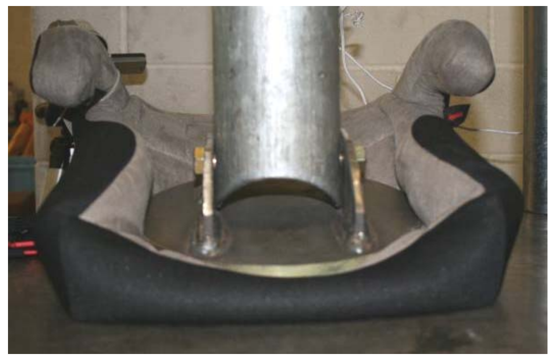

Figure 2. **Harmony Youth BPB.**

Figure 3. **Bubble Bum BPB.**

Figure 4 shows one of the BPBs that complied with the Canadian requirement.

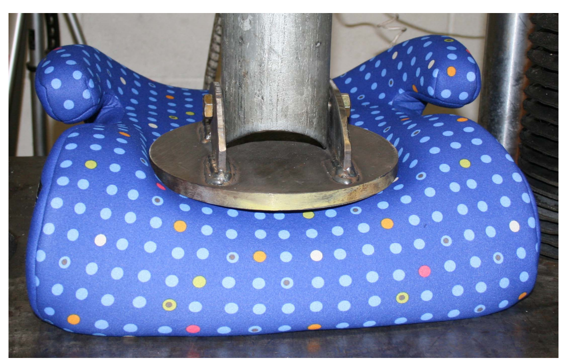

Figure 4. **Volvo BPB.**

DISCUSSION

Before the introduction of BPBs, children who outgrew child safety seats would sit directly on the vehicle seat and use the adult seat belts for crash restraint. These adult seat belts, however, did not properly fit children and frequently caused serious injury, particularly abdominal and lower spinal injuries from loading by the lap belt. Belt-positioning-boosters (BPB) seats were introduced to improve the fit of the adult lap/shoulder seat belt when used by children. After introduction of BPBs, however, it was observed that their use did not reduce the frequency of abdominal injuries.[47] Many of these early BPBs had highly compressible seating surfaces lacked structural anti-submarining seat ramps and lap belt guide hooks. The evaluation and testing of BPBs conducted by the authors indicates that since then, the majority of BPBs introduced incorporate seating surfaces with low compressibility and anti-submarining seat ramps. The majority also incorporate lap belt guide hooks. These features combine to minimize the potential for submarining by limiting forward and downward movement of the pelvis and providing a restraining force to the bottom of the pelvis that counters the lap belt force applied to the top of the pelvis. Two of the BPBs evaluated, however, had very little or no seat ramp and, therefore, did not provide any significant restraining load to the pelvis. One of those two BPBs, the Harmony Youth, also had an extremely compressible seating surface. Previous research indicates that these deficiencies significantly increase the potential for submarining.[48,49,50,51,52,53,54,55,56]The Bubble Bum, which was discovered late in the study and therefore only subjected to the Canadian Compression testing was also highly compressible and lacked a seat ramp structure.

One BPB evaluated and tested, the Britax Parkway, in addition to incorporating an anti-submarining seat bottom ramp and low compressibility incorporated an Anti-Submarining Clip (ASC). The ASC attaches to a strap secured to the center of the BPB seat bottom. After a child occupies the BPB and secures the lap/shoulder belt, the clip is attached to the center of the lap belt and adjusted snug. The ASC acts as a crotch strap to hold the lap belt down on the pelvis. Brown reported that during frontal crash sled testing, “These crotch strap–like devices held the lap belt down throughout the impact.”[57] The Bubble Bum BPB incorporates lap belt hooks on the outboard sides of the booster to hold the lap belt down, similar to lap belt guide hooks. As with the Britax Parkway’s ASC, one of these belt hooks would have to be attached and detached each time the child donned and doffed the seat belt, making it highly likely that these hooks will often not be used. With the Britax Parkway, the ASC is supplemental to the passive anti-submarining features that the Parkway incorporates, i.e., seat ramp, low compressibility, and lap belt guide hooks. The Bubble Bum does not incorporate these features and is totally reliant on the belt hooks to be used to prevent submarining.

Modern rear seat automotive restraint systems consist of a lap/shoulder belt and seat and are often supplemented with side impact protective inflatable devices. To work effectively and avoid submarining injuries, the seat belt and seat must be designed to work together to balance the forces applied to the occupant’s pelvis. For the adult occupant, this can be readily accomplished because the vehicle manufacturer has complete control over the both the seat belt and seat design. For a child who has outgrown a conventional child safety seat and is using the adult lap/shoulder belt with an add-on BPB seat, the vehicle manufacturer has no control over the design of the BPB. There are no requirements pertaining to the design or performance of the BPB seat bottom relative to its restraining the pelvis. Therefore, the ability of BPBs to balance the forces applied to the pelvis varies significantly. Requirements need to be incorporated into FMVSS 213 that will enable vehicle manufacturers to rely on the BPB to complement the seat and seat belt to ensure that submarining is avoided.

Hybrid III (HIII) dummies have been found to be too stiff in the lumbar region. This stiffness prevents pelvic rotation and therefore prevents the dummy from submarining under circumstances that a human child would.[58] Therefore, dynamic testing with the HIII dummy cannot be relied upon to determine if a system allows submarining.

Due to children’s immature anatomy and tendency to get out-of-position, it is recommended that children remain in forward-facing CSS incorporating five-point harnesses for as long as possible. Fortunately, there are now such CSSs readily available for children up to 36.3 kg (80 lbs) and 1346 mm (53 inches). For children transitioned to a BPB, BPBs incorporating an anti-submarining clip appears to be an effective countermeasure to ensure submarining is prevented.

To maximize the effectiveness of the seat ramp, the ramp must remain in position during the crash. The majority of BPB on the market do not attach to the vehicle. Some BPBs incorporate high friction material on the bottom to minimize movement. A few BPBs incorporate the ability to secure to the vehicle using the lower LATCH anchorages. This feature ensures the BPB remains in proper position, not only during frontal crashes, but also in all crash modes, including rollover. During a rollover crash, an unattached booster could get out of position or come out from under the child completely, compromising the fit and performance of the lap/shoulder belt. In side impacts, researchers have found that an unattached BPB will move more readily, reducing the effectiveness of any side wing restraint provided with the BPB and that it is feasible to develop a BPB incorporating rigid LATCH anchorages that significantly improves the BPB's side impact protection.[59]

CONCLUSIONS

Published epidemiology studies indicate that BPBs generally reduce the rate of injury to children in crashes compared to children using only the adult seat belt. However, children continue to sustain "seat belt syndrome" injuries. Research has determined that seat design is critical to avoiding submarining the lap belt and preventing seat belt syndrome injuries. Children are especially vulnerable to submarining the lap belt. Yet, there are no requirements to ensure that BPBs incorporate features that have been identified as critical to avoid submarining the lap belt during frontal crashes. These features include anti-submarining seat bottom ramps, low compressibility seating surfaces, and effective lap belt guide hooks. There are BPBs on the market in the U.S. that fail to incorporate an anti-submarining design. Their high seating surface compressibility, lack of ramp, and lack of effective lap belt guide hooks promote submarining of the lap belt. BPB manufacturers, automobile manufacturers, and NHTSA must work together to establish requirements that will ensure that the BPB will work properly with motor vehicle seat belts to prevent submarining and its associated injuries.

STUDY LIMITATIONS

This study evaluated a sampling of BPBs on the U.S. market since the 1980s. It did not include all BPBs currently available in U.S.

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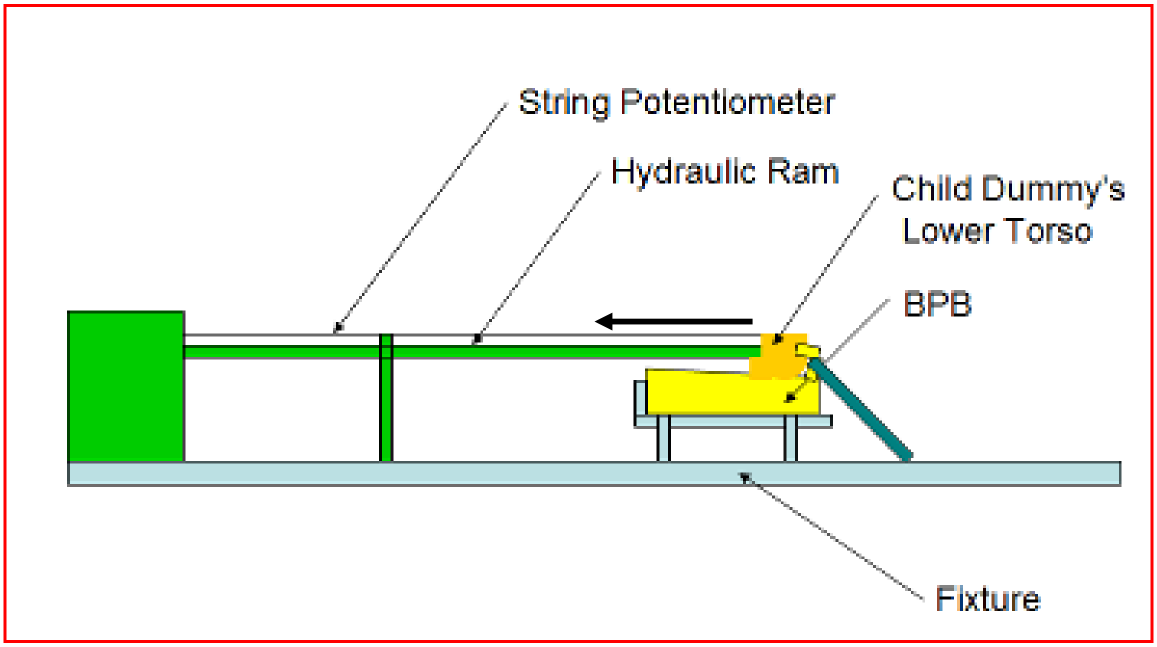
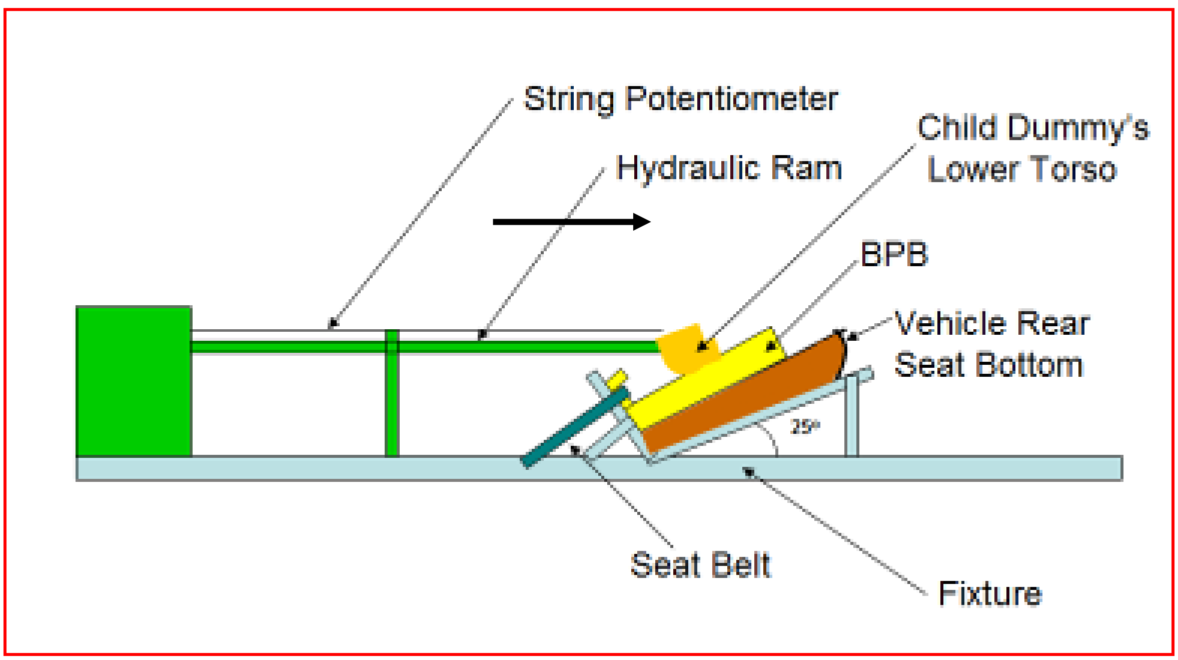
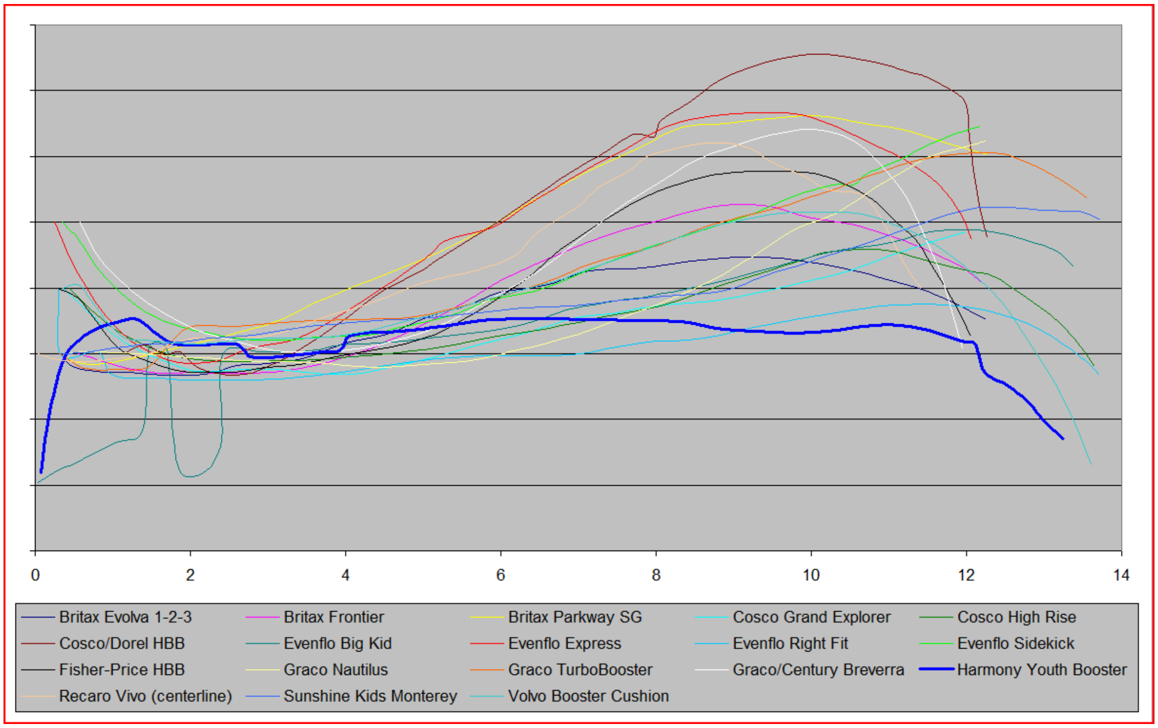
APPENDICES



Appendix A. BPB Seat Surface Pelvic Restraint Test Set-up.



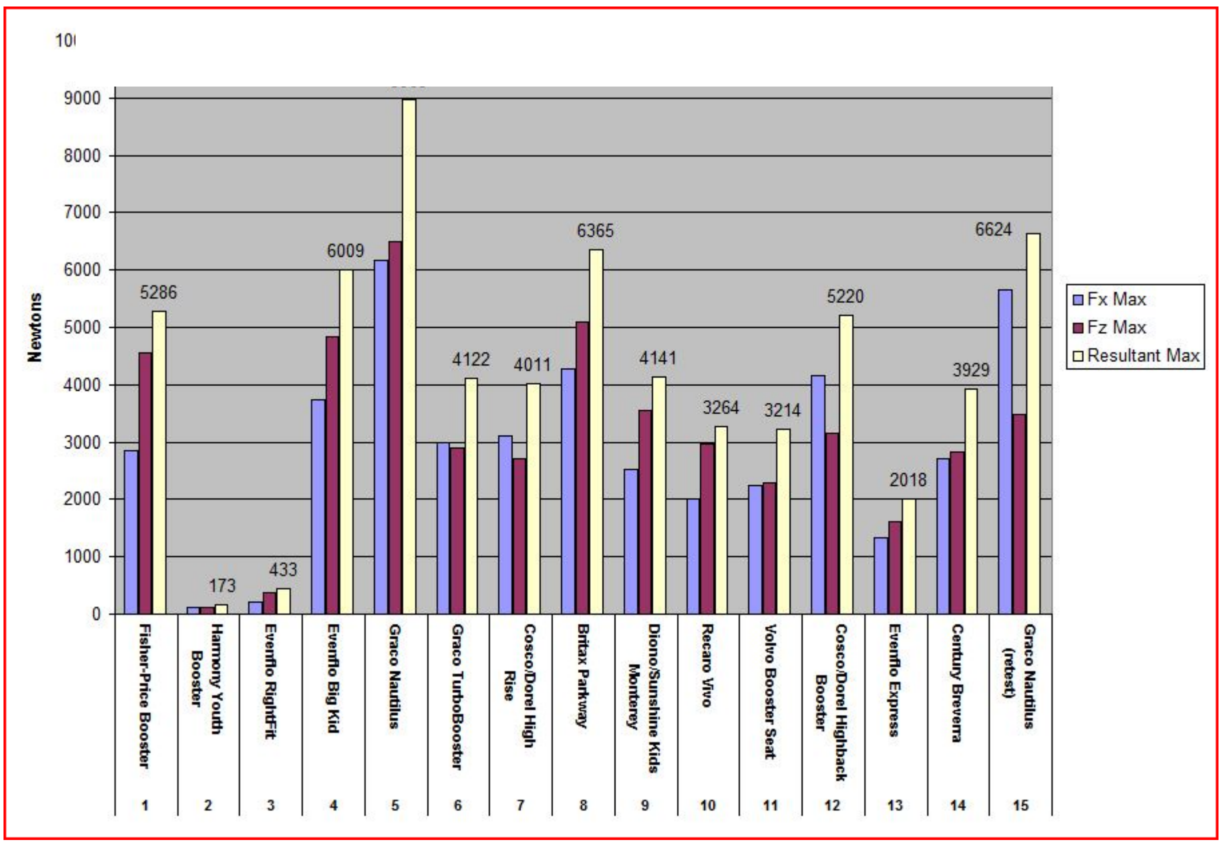
Appendix B. BPB Seat Bottom Compression Test Set-up.



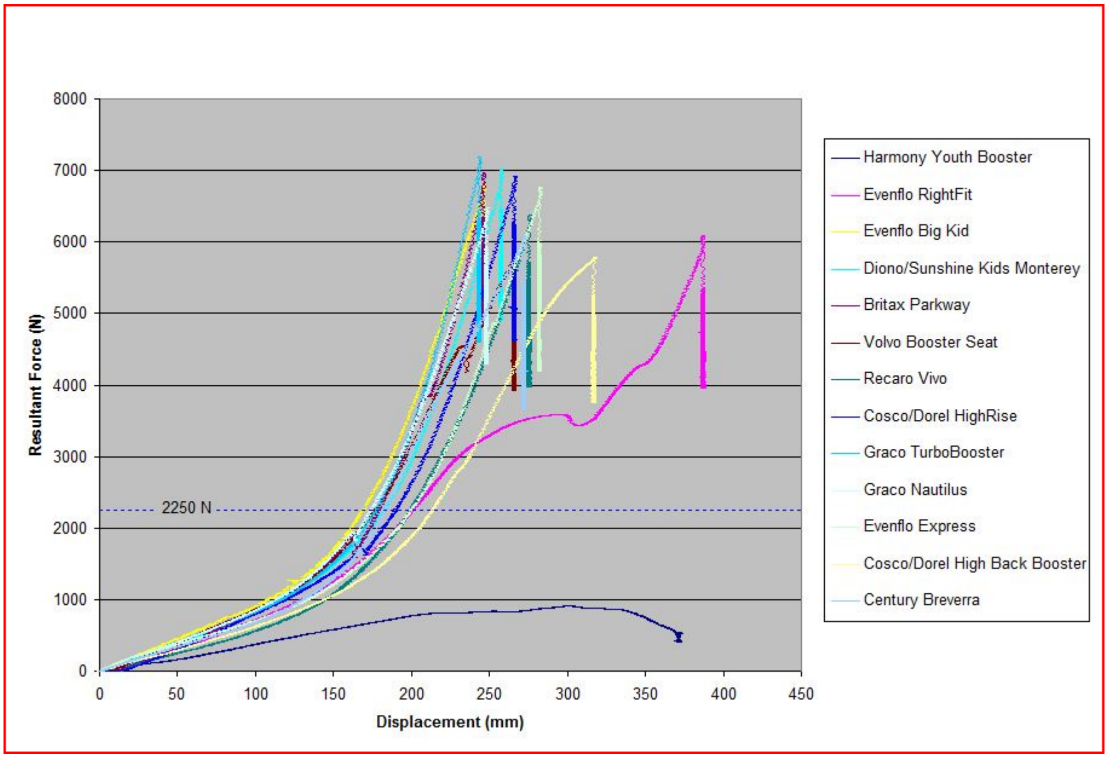
Appendix C. BPB Seat Surface Contours.

BPB Make/Model	Seat Bottom Fore/Aft Depth, (mm)	Angle at 152 mm (6") (degrees)	Angle at 203 mm (8") (degrees)	Angle at 254 mm (10") (degrees)	Angle at 305 mm (12") (degrees)	Maximum Angle
Volvo Booster Cushion	362 (14¼")	10	12	0	-27	12
Evenflo Sidekick	400 (15¾")	9	11	11	12	12
Cosco Grand Explorer	400 (15¾")	7	6	8	8	8
Graco/Century Breverra	363 (14¼")	12	16	0	-	16
Evenflo Right Fit	363 (14¼")	3	4	6	-5	6
Fisher Price Safe Embrace	381 (15")	18	12	-12	-	18
Dorel/Cosco Highback	381 (15")	19	16	3	-28	19
Evenflo Express	289 (11-3/8")	17	10	-7	-	17
Dorel Highrise	394 (15½")	6	8	11	-14	11
Graco Turbo Booster	394 (15½")	7	10	9	2	10
Evenflo Big Kid	362 (14¼")	6	7	8	1	8
Britax Parkway	356 (14")	13	15	18	-2	18
Graco Nautilus	311 (12¼")	8	14	18	12	18
Recaro Vivo	311 (12¼")	7	6	3	-	7
Sunshine Kids Monterey	324 (12¾")	6	8	12	14	14
Britax Frontier	305 (12")	15	5	-5	-19	15
Britax Evolva	356 (14")	12	8	-4	-15	12
Harmony Youth	368 (14½")	3	-1	-1	-16	3
Average	356 (14")	9.9	9.3	4.3	-5.5	12.4

Appendix D. BPB Seating Surface Angle along the Longitudinal Centerline (at various points from the back edge of the BPB).



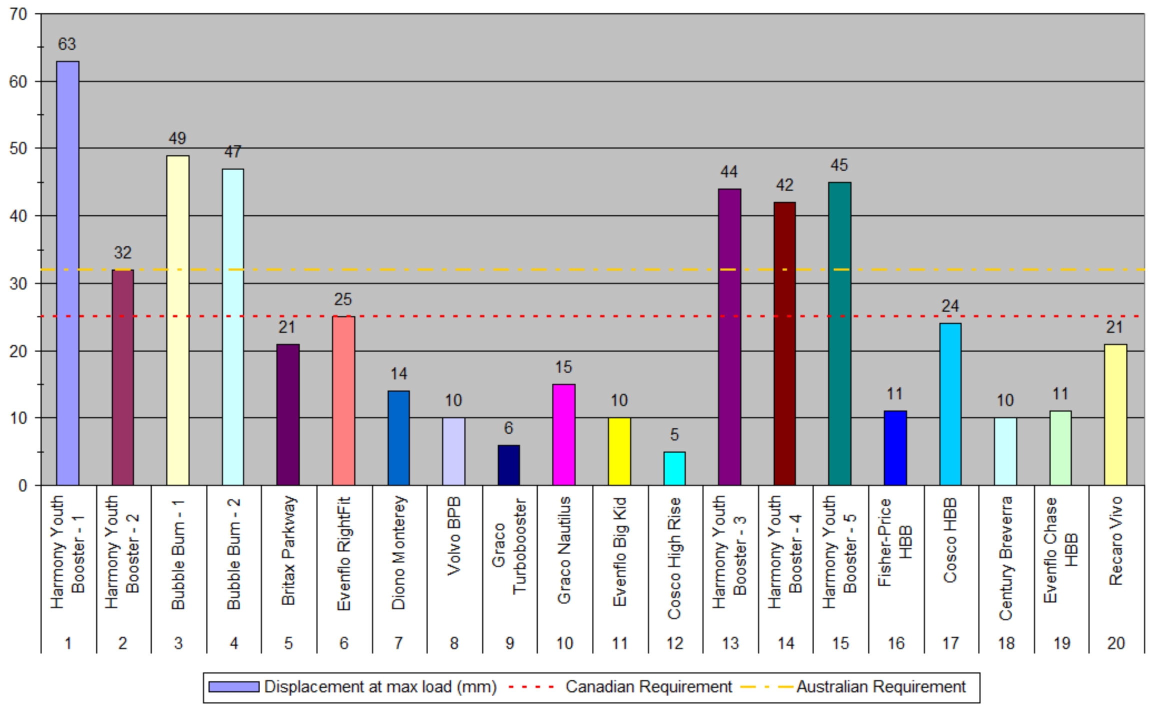
Appendix E. Maximum Load Generated During Seat Bottom Pelvic Restraint Testing.



Appendix F. BPB Seat Bottom Compressibility Testing Force-Deflection Curves.

Test No.	Make/Model	Model Number	Date of Manufacture	Test Result (mm)	Pass/Fail (>25mm)
1	U.S. Harmony/Youth	0304003LRW	09/06/10	63 (2.5”)	Fail
2	U.S. Harmony/Youth	0304003LRW	09/06/10	32 (1.25”)	Fail
3	Bubble Bum/Booster	BB001US	11/30/11	48 (1.9”)	Fail
4	Bubble Bum/Booster	BB001US	11/30/11	46 (1.8”)	Fail
5	Britax/Parkway	E9LA869	7/11	21 (0.8”)	Pass
6	Evenflo/Right Fit	2451184	08/14/01	25 (1”)	Pass
7	Diono/Monterrey	US15000	10/11	14 (0.55”)	Pass
8	Volvo/Booster	9451523	98	10 (0.4”)	Pass
9	Graco/Turbo Booster	1747302	6/10/11	6 (0.25”)	Pass
10	Graco Nautilus	1757842	08/01/09	15 (0.6”)	Pass
11	Evenflo Big Kid	3091982A	07/13/10	10 (0.39”)	Pass
12	Cosco High Rise	22297-A06	1/11/11	5 (0.20”)	Pass
13	U.S. Harmony Youth	0304003HCM	03/27/12	44 (1.75”)	Fail
14	U.S Harmony Youth	0304003WPK	07/19/10	42 (1.65”)	Fail
15	U.S. Harmony Youth	0304003CCE	09/01/11	46 (1.8”)	Fail
16	Fisher Price	79750	11/30/97	11 (0.43”)	Pass
17	Cosco High Back	023377	03/22/10	24 (0.94”)	Pass
18	Century Breverra	4865ABN	12/07/98	10 (0.39”)	Pass
19	Evenflo Chase	32911113	04/04/12	11 (0.43”)	Pass
20	Recaro Vivo	351.00.ME19	03/26/12	21 (0.83”)	Pass
21	Canadian Harmony Youth	0304004LRC	05/19/12	25.3 (1.00)	Fail
22	Canadian Harmony Youth	0304004LRC	05/19/12	27 (1.06)	Fail
23	Canadian Harmony Youth	0304004LRC	02/10/12	20 (0.87)	Pass
24	Canadian Harmony Youth	0304004LRC	05/19/12	26 (1.02)	Fail

Appendix G. CMVSS Seat Surface Compressibility Testing.



Appendix H. CMVSS Seat Surface Compressibility Test Results.