Child Occupant Protection in Buses and Coaches: A Parametric Study of Restraint Systems in Frontal Crashes

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Objective:

The newly approved UN Regulation No. 170 addresses the proper protection of children in buses and coaches. This study aims to evaluate the head kinematics and spinal loads of 3- and 6-year-old child human body models with and without a child restraint system (CRS) in bus seats under frontal crash scenarios for buses and coaches, in light of the new UN regulation. .

Methods:

A parametric computational study was conducted using the PIPER Human Body Model (HBM) to represent both a 3-year-old and a 6-year-old child. The HBM was seated in a bus seat, with and without a booster seat, and exposed to a frontal collision scenario. 14 conditions were simulated: 2 child sizes, x 2 belt systems (2-point and 3-point) x 3 CRS conditions (none, booster seat without harness, booster with ISOFIX), + unrestrained with each child size (n=2). A delta-v of 30 km/h was applied in accordance with UNECE R80 and R170. Head kinematics and spinal loads were assessed. .

Results:

The 2-point seatbelt configurations for 3-year-old and 6-year-old child models resulted in head excursions exceeding 550 mm, even with a booster seat, potentially leading to head contact with the forward seat. In contrast, 3-point seatbelts (with and without a booster seat) reduced these excursions to 205-321 mm for 3-year-olds and 229-316 mm for 6-year-olds compared with the 2-point configuration. The most effective configuration was the 3-point seatbelt paired with a booster seat, which further reduced head excursion by 77-109 mm compared to non-booster seat setups. The integration of ISOFIX anchorages showed only marginal improvement (about 10mm) in head excursion reduction compared to non-ISOFIX installations. .

Conclusions:

This research highlights that 2-point seatbelts in buses and coaches may be insufficient to provide adequate restraint for child occupants, leading to excessive head excursion in frontal crashes. Conversely, 3-point seatbelts combined with booster seat effectively managed occupant kinematics, preventing contact with the interior environment. Although ISOFIX offered some benefits, the most significant factor in reducing injury risk is the transition from 2-point to 3-point seatbelts. Further studies focusing on younger children and other child restraint systems may be needed to fully evaluate their safety. .

Keywords: UN R170, Children, buses, coaches, PIPER HBM, CRS .

INTRODUCTION

Road traffic accidents involving buses and coaches, although relatively infrequent, raise significant safety concerns due to the potential impact on a large number of passengers (Jamroziak et al. 2020). Child restraint systems (CRSs) are effective in reducing injuries and fatalities for children in motor vehicle crashes. Previous studies have shown 80% lower odds of sustaining an injury when using a CRS for children aged 2-3 years compared with a seatbelt (Zaloshnja et al. 2007), and 78% lower odds of serious injury when using a forward-facing (FF) CRS for children aged 12 to 47 months (Arbogast et al. 2004). More recent evidence confirms the relevance of CRS use in child passenger safety. (Sartin et al. 2024) showed that CRS mitigated child passenger injury risk in a linked crash- and hospital-record study. European paediatric trauma data indicate that road traffic accidents remain a major source of severe paediatric trauma, with head/neck injuries frequently reported and restraint or protective-device non-use (45%) or misuse (13%) still present (Castelão et al. 2023).

The safety of passengers in large passenger vehicles, such as coaches and buses, is governed by various international and national regulations. The UNECE R80 specifically establishes safety requirements for coach seats, focusing on adult occupants, but serving as a foundational standard for national norms addressing child safety in buses, such as China's GB24406 for school bus seats (Jamroziak et al. 2020; Li et al. 2020). UNECE R80 states that dynamic tests may be performed to simulate a frontal impact, in which seats with 50^{th} percentile adult male anthropomorphic test devices (ATDs) are subjected to deceleration pulses (Jamroziak et al. 2020). This regulation obliges the provision of two-point (2P) or three-point (3P) safety seatbelts in new buses and coaches. The newly approved UN regulation, UNECE R170, to assess the protection of children in buses and coaches, came into effect on June 20, 2024, under the 1958 Agreement (United Nations (UN) 2024). This regulation establishes a type-approval testing scheme for CRS in buses and coaches. UNECE R170 outlines important requirements for both forward- and rearward-facing CRS. Additionally, it ensures compatibility with built-in seatbelts or ISOFIX anchorages to limit the CRS forward displacement, allowing the use of child seats approved under other regulations, such as UNECE R129.

The topic of 2P or 3P seatbelt installations in buses has received attention with regard to the safety of adult occupants. Previous research on the use of the 2P seatbelt in buses and coaches has indicated an increased risk of head and neck injuries during severe frontal crashes. This is primarily due to the head striking the seat back at high speeds (Hinch et al. 2002; Peleg and Goldman 2008). Jamroziak et al. (2020) found that these seatbelt systems in coaches did not meet injury criteria standards, as "high values of acceleration were recorded at the center of gravity of the head." Moreover, this increase in injury risk may also lead to an increased incidence of thoracic injuries (Albertsson and Falkmer 2005), as well as internal injuries and abdominal contusions in school buses (Peleg and Goldman 2008).

Jamroziak et al. (2020) found that only a 3P seatbelt system meets all safety criteria for children in coaches during frontal impacts, as defined by UNECE R80 and R94. This finding supports the increased injury and contact risk observed for 2P seatbelt systems mentioned above. Later, Tingting Sun et al. (2025) also observed that 3P seatbelts protected the heads and necks of both adults and children in coaches.

Martínez et al. (2011) have focused on the effect of different seatbelt systems and the use of CRS for coaches. A 2P seatbelt, a 3P seatbelt, a 3P seatbelt with an adjustable d-ring height, and a 3P seatbelt with a CRS were used with four child ATDs for frontal crashes at 30 km/h. The CRS used in this case was an FF CRS and booster seat without a seatback, selected for the appropriate child size. The joint use of a coach seat with a 3P seatbelt, in conjunction with the specific CRS, has been the only system capable of properly retaining all occupants (1.5, 3, 6, and 10 YO ATDs). The 3P seatbelt, with and without regulation of the d-ring height, reduces injury risk relative to the 2P seatbelt, but not across all ages. The 3P seatbelt alone was incompatible with children younger than 6 years old (6YO), and the d-ring height adjustment reduced this incompatibility to younger than 3 years old (3YO). To the authors' knowledge, no other study has assessed the effect of CRS on children in buses and coaches.

Limited evidence is available on how different restraint configurations affect child occupants in bus/coach frontal-impact conditions. 2P and 3P belt systems differ in the degree of upper-body restraint they provide. While head excursion is directly influenced by the restraint system's capacity to limit forward motion, cervical and lumbar spine loads may also vary depending on belt routing, occupant size, and booster use. Therefore, a comparative assessment of both head kinematics and spinal loading is needed to characterize the biomechanical implications of different restraint configurations in buses and coaches.

This study aims to evaluate the head kinematics and spinal loads of 3- and 6-year-old child human body models in bus seats under frontal crash scenarios for buses and coaches. The analysis compares unbelted occupants with children restrained by 2P or 3P seatbelt systems, with and without booster seat use.

METHODS

A computational model was assembled by combining a child HBM, booster seat, bus seat, and seatbelt. This model was used with LSDYNA Version mpp s R12.2.2.

Child HBM

The PIPER scalable child HBM is an open-source finite-element model developed as part of the PIPER EU project (Beillas et al. 2016). This model was developed to estimate children's biomechanical response and their behaviour in impact scenarios. Two versions of the HBM were used to create the simulation model: the baseline PIPER model, representing an average 6-year-old child (6YO) with a total mass of 23 kg and height of 1127 mm, and a scaled model of a 3-year-old child (3YO) with a mass of 16 kg and height of 952 mm. The scaled model was derived using the PIPER software developed within the same project.

Child Restraint System

The Open Access Child Seat (FE_models / Open Access Child Seat · GitLab 2022) was used to secure the child models. This model was developed as part of the Virtual project and is available on the Open VT platform. This booster seat features a seatback and resembles Dorel's "RodiFix"; it also complies with UN R44 regulations for children weighing 15-36 kg. This model does not include a 3-point or 5-point harness for child restraint. Modifications were made according to the instructions on the OpenVT platform to accommodate both child sizes. Additionally, the seat allows the booster to be secured to the vehicle's structure via an ISOFIX attachment.

Bus Model and Acceleration Pulse

The interior of the bus was based on a model developed by the INSIA (Instituto Universitario de Investigación del Automóvil, Universidad Politécnica de Madrid, Spain) within the VIRTUAL project. Two-seat rows were included, with spacing based on measurements of the IVECO EVADYS bus. The distance between the seat rows was set at 750 mm. It should be noted that this distance can vary depending on the bus configuration. To avoid including results applicable only to one seating configuration, the contact between the front seat row and the HBM/booster was not considered in this study. Deactivating this contact allows comparison of occupant kinematics across different restraint conditions without the influence of the variable front seat position.

A frontal crash acceleration pulse was applied to the bus model. The frontal acceleration pulse was derived from UNECE R80 and UNECE R170, featuring a velocity change of 30 km/h and a pulse shape within the specified corridor of the regulations. The pulse was applied for 150 ms, matching the simulation time. The pulse was obtained to achieve a delta-v of 30 km/h and to reach the following values: 0 g at 0 ms, 9 g at 15 ms, 8 g at 90 ms, and 0 g at 120 ms (maintaining the same acceleration until the end). A linear interpolation was performed between all the specified points, as shown in Figure 1.

Restraint System and Simulation Matrix

Table 1 summarizes the simulation matrix. The following paragraphs provide a detailed description of this simulation matrix and clarify the meanings of the abbreviations in the table.
Three seatbelt configurations were combined with three booster seat configurations to form the simulation matrix used in the study. The seatbelt configurations included belted occupants using 2-point (2P) and 3-point (3P) seatbelts. Anchor points were rigidly fixed to the bus structure. The 3P seatbelt was routed through the seat backrest, which was modelled as rigid. The anchor of the seatbelt at the starting point, before the d-ring and the end-bracket, included the simplified retractor model from THUMS User Community (TUC project), with the pre-tensioner and load limiter deactivated. Seatbelt webbing was based on the Autoliv simplified seatbelt model with a 48 mm width.

The unbelted child configuration (i.e., the Unrestrained configuration) was included as a reference for evaluating occupant displacement relative to other configurations. This setup was simulated without a booster seat.

The 2P and 3P seatbelt configurations were simulated with no booster seat (No Booster), with a booster seat (Booster), and with a booster seat and ISOFIX (Booster+ISOFIX). The same booster seat position was used to route both seatbelt configurations. In the 2P configuration, the shoulder seatbelt section was removed, and the ISOFIX attachment was fixed in place when it was included.

The child’s head kinematics from the simulations was assessed using: head excursion, head exceeding 550 mm from the Cr seat point (i.e., the point where the seat cushions of the seatback and seatpan meet), which is required by the UNECE R170, and whether contact with the front row of seats was anticipated. Spinal loads (forces and moments) were assessed at the T1 cervical vertebra and the lumbar intervertebral discs: L1-L2, L2-L3, L3-L4, and L4-L5.

Child positioning method

Both child models were positioned in two stages: first, a leg-straightening simulation using the marionette method, followed by a gravity-settling simulation. During the latter, the pelvis and torso were constrained relative to each other, while the model was allowed to move downward toward the booster seat and the bus seat. The model was seated in an upright position with minimal slouch (Miller et al. 2021) across all configurations, with no further changes.

RESULTS

A total of 14 simulations were carried out using the PIPER HBM across two anthropometries (3YO and 6YO), with No Booster, Booster, and Booster+ISOFIX, in a bus seat without a seatbelt and with a 2P and 3P seatbelt. This section shows the results for each HBM anthropometry and restraint condition. Figure 2 shows the positioned models for the 3YO and 6YO PIPER HBMs, with and without a booster, using a 3P seatbelt. Figura A1 (Appendix) displays all the maximum excursions for the child model and the restraint condition.

3YO PIPER HBM

Overall kinematics of the PIPER HBM using 2P and 3P seatbelts at 150 and 100 ms, respectively, are shown in Figure 3. Different timeframes were chosen for each configuration to show the displacements occurring around the time of peak forward head excursion. Configurations with no booster, booster, and Booster+ISOFIX are shown in green, blue, and orange, respectively. While the initial position of the child's head without a booster seat was 56 mm farther back and 95 mm lower, the final posture for all restraint combinations shows similar excursions (max. 70 mm difference at the top of the head) and leaning angles, indicating that the amount of pelvic/head excursion is substantially larger in the absence of a booster seat. Neither ejection from the seat nor booster was observed during the frontal crash of the 3YO PIPER model. Submarining was also not observed for any of the studied restraint configurations.

Peak forward excursion of the 3YO child's head in the baseline configuration was 789 mm at 150 ms, with the whole body moving close to a rigid body forward. Table 2 summarizes head kinematics results for the 2P and 3P seatbelt models, with the latter shown in bold. Using a seatbelt without a booster seat reduced head excursion by 72 and 468 mm for the 2P and 3P seatbelts, respectively, to 717 and 321 mm. When all the different 2P seatbelt configurations were switched to a 3P seatbelt, a reduction from 396 to 443 mm was observed. Furthermore, all the 2P seatbelt configurations showed the head exceeding the 550 distance to the Cr point and an expected contact with the front-row seat, while all 3P seatbelt configurations did not. When keeping the same seatbelt configuration and switching to a Booster configuration, head excursions were reduced compared with using only the seatbelt. The use of the booster seat resulted in a 69-116 mm reduction, but including ISOFIX did not show a clear difference, with -33 and +12 mm if a 2P or 3P seatbelt was used.

Table 3 presents the results for the atlanto-occipital joint at the neck and lumbar spine loads, including Fz (axial force), Fx (shear force), and My (bending moment) in that order. As with the previous table, results highlighted in bold indicate the findings related to the 3P seatbelt configuration.

Switching to a 3P seatbelt configuration generally reduced Fx (up to 0.5 kN), Fz (up to 0.1 kN), and My (up to 10.5 Nm). However, in some cases, Fz and Fx increased by up to 0.1 kN, and My increased by up to 2.3 Nm. The impact of including ISOFIX was inconsistent across vertebral levels, ranging from increases to decreases.

6YO PIPER HBM

Figure 4 shows the excursions of the 6YO PIPER HBM using 2P and 3P seatbelts at 150 and 100 ms, respectively. The same configurations and colours as with the 3YO PIPER model were used in the figure. While the initial position of the child's head model without a booster seat was 50 mm farther back and 99 mm lower, the final posture for all booster combinations shows similar excursions (max. 70 mm difference at the top of the head) and leaning angles. Neither ejection from the seat nor booster was observed during the frontal crash of the 6YO PIPER model. Submarining was also not observed for the belted child configurations.

Peak forward excursion of the 6YO child's head in the baseline configuration was 786 mm at 150 ms. Table 4 summarizes head kinematics results for the 2P and 3P seatbelt models, with the latter shown in bold as with the 3YO model. Using a seatbelt without a booster seat reduced head excursion by 29 and 470 mm for the 2P and 3P seatbelts, respectively, to 757 and 316 mm. When all the different 2P seatbelt configurations were switched to a 3P seatbelt, a reduction from 441 to 473 mm was observed. Furthermore, as with the 3YO model, all 2P seatbelt configurations showed the head exceeding the 550 distance to the Cr point and an expected contact with the front-row seat, whereas none of the 3P seatbelt configurations showed a similar outcome. When keeping the same seatbelt configuration and switching to a Booster configuration, head excursions were reduced compared with using only the seatbelt. The use of the booster seat resulted in a 55-87 mm reduction, but including ISOFIX with the 3P seatbelt showed a larger excursion (10 mm) compared with the booster seat without ISOFIX. The comparison for the 2P seatbelt with Booster+ISOFIX was not possible because the simulation stopped at 105 ms, due to a simulation error.

Table 5 presents the results for neck and lumbar spine loads for the 6YO PIPER model, in the following order: Fz (axial force), Fx (shear force), and My (bending moment). As with the previous table, results highlighted in bold indicate the findings related to the 3P seatbelt configuration.

The impact of switching from a 2P to a 3P seatbelt varied by vertebral level and booster seat configuration. Generally, the 3P configuration is associated with reductions in Fz (up to 0.4 kN) and My (up to 12 Nm), with the most significant decreases observed in the lower lumbar spine when a booster seat is used. In contrast, the Fx often remained unchanged or increased slightly with the 3P seatbelt, particularly in scenarios without a booster seat. Additionally, the cervical spine experiences increased forces and moments when using the 3P seatbelt.

When comparing restraint configurations within the same seatbelt type, adding a booster seat typically results in higher lumbar Fx and My for the 2P seatbelt (increases of up to 0.2 kN and 2.6 Nm, respectively). However, for the 3P seatbelt, the addition of a booster seat leads to near-zero lumbar Fz but a mixed response in My. Incorporating ISOFIX with the booster under the 3P seatbelt slightly reduces lumbar Fx (about 0.1 kN) and generally lowers My (up to 2.4 Nm) at the L1–L2 level, despite a small increase (0.2 Nm) in the moment at the L4–L5 level.

These patterns contrast with the results for the 3YO model, in which the 3P seatbelt consistently reduced loads. For the 6YO model, while there were greater reductions in lower lumbar moments, these were offset by an increase in shear force in the lumbar region. Furthermore, booster seat configurations that reduced lumbar moments also increased load at C1.

Finally, the case of the 2P Booster with ISOFIX should be interpreted with caution, as the simulation terminated at 105 milliseconds, suggesting that the indicated values may underestimate peak loads compared to the 150-millisecond window. This simulation was repeated several times, but the logs did not clearly indicate the error. Furthermore, d3plots and signals from the binout were inspected, and no clear reason for the failure was found.

DISCUSSION

This study evaluates the kinematics and spinal loads of child occupants during frontal impacts in buses and coaches, in accordance with UNECE R80 and aligned with the type-approval tests of UNECE R170 (United Nations (UN) 2024). Regardless of the HBM age (3YO and 6YO), switching from a 2P to a 3P seatbelt had the greatest effect on occupant kinematics. The use of 2P seatbelts resulted in head excursions exceeding 550 mm Cr distance threshold, indicating potential head contact with the seat in front. This means that none of the 2P seatbelt configurations would meet the requirements of UNECE R170 for either child anthropometry. In contrast, 3P seatbelts limited head movement to below this threshold, a finding consistent with previous research (Hinch et al. 2002; Albertsson and Falkmer 2005; Peleg and Goldman 2008; Martínez et al. 2011; Jamroziak et al. 2020; Tingting et al. 2025). Furthermore, adding a booster seat further minimized head excursion, whereas ISOFIX showed only slight changes across the tested configurations.

Controlling the child excursion when selecting the restraint system appeared to be more effective for injury prevention than focusing solely on load reduction in the child model when there is no contact between the child and the bus interior. This observation aligns with previous research indicating that 2P seatbelts can result in a kinematic that increases the risk of head and neck injuries due to head-to-seatback interactions (Hinch et al. 2002; Peleg and Goldman 2008; Martínez et al. 2011). Although the child occupant contact with the front row seat was not included, the 2P seatbelts showed an occupant kinematic that overcomes the 550 mm Cr threshold and suggests head-to-seatback contact. A more detailed and validated seat interior may reveal injury criteria patterns similar to those found in previous studies on head accelerations and neck forces.

The observed benefit of 3P restraint is consistent with coach literature reporting improved protection of the head and neck for belted occupants, including children. In addition, Martínez et al. (2011) reported that the joint use of a coach seat with a 3P seatbelt and a booster seat was the only system that properly retained all child ATDs in their test matrix, highlighting the importance of combining upper-torso restraint with appropriate seating/booster solutions. Furthermore, the seatbelt for the 3P configuration was fastened, and the belt strand fell naturally very close to the child's neck, similar to the findings of Martínez et al. (2011) with the seatbelt alone. Although this may have led to greater neck forces, the increment was not observed for the T1 cross-section force sensor in this study.

A notable difference observed is that Martínez et al. (2011) found that 3P seatbelts alone were insufficient for younger children under certain seatbelt geometries, which they addressed using a d-ring that regulates its height. In the present simulations, 3P seatbelts without a booster seat maintained head excursion below the 550 mm threshold for both age groups. However, the current study uses a booster seat with a seatback, whereas Martínez et al. (2011) utilized a booster seat without one. This suggests that variations in seatbelt routing, anchorage geometry, and the interaction between the seat and booster may alter the boundary between "acceptable" and "insufficient" restraint performance. This difference may result in a booster seat that passes type approval tests but is only suitable for specific bus models.

The additional excursion reduction observed when adding a booster seat is directionally consistent with the established effectiveness of CRS in reducing injury risk compared with seatbelt-only restraint in passenger vehicles (Arbogast et al. 2004; Zaloshnja et al. 2007). Although UNECE R170 explicitly addresses CRS compatibility with both built-in seatbelts and ISOFIX, ISOFIX produced only small changes in head excursion in the present configuration. This outcome suggests that, for this seat, seatbelt routing and booster design, global kinematics were primarily governed by the presence of an upper-torso restraint (3P vs 2P seatbelt) and by CRS geometry, rather than by the anchorage method alone. However, ISOFIX effects may be more pronounced under different installation conditions, seat stiffness characteristics, or loading directions, as rollover-focused work has shown that restraint details can be decisive for containment in dynamic rotational tests (Cruz-Jaramillo et al. 2020). Although they are not required by UNECE R170, they could be an important tool in preventing misuse (Cicchino and Jermakian 2015).

Beyond head excursion, cervical and lumbar loads provide complementary evidence of how restraint configuration redistributes inertial loads along the spine. This aspect is particularly relevant for child occupants because cervical loads for the 3YO ATD (Q3) are not required to be reported in UNECE R129 or R170, and corresponding injury metrics have not been defined (UNECE 2013; CLEPA 2020). In the absence of regulatory limits, published tolerance data provide a useful interpretive frame: child cervical spine failure tensile forces have been reported in the range 494–918 N (Ouyang et al. 2005), with estimates around 700 N and 900 N for a 3YO and 6YO based on age-dependent modelling (Luck et al. 2013). Although simulations showed an increase of 0.1 kN to 0.3 reaching up to 0.3 kN when switching to a 3P seatbelt, these results were below the injurious limits mentioned above.

Neck loading also remains relevant when head contact is not explicitly modelled, because serious head and cervical injuries have been documented in well-restrained young children. This can be observed in non-contact cases where head injury was associated with neck tension at relatively high impact severity (Sherwood et al. 2003; Bohman et al. 2011). Although UNECE R80 contemplates using the front seat row as a restraint system for unbelted adult occupants, this approach may not be feasible for children, as younger occupants may directly strike the seat back with the head, leading to head, neck, and/or thoracic injuries (Hinch et al. 2002; Albertsson and Falkmer 2005; Peleg and Goldman 2008; Jamroziak et al. 2020).

Across configurations, lumbar force ranged from 0.0 to 0.5 kN for Fz and reached moments from 0.5 to 13 Nm in the child models. The largest moments generally occurred under 2P configurations, and the lowest moments under 3P+Booster, where lumbar Fz also tended toward near-zero. Although some dynamic injury tolerances have been investigated for adult occupants (Tushak et al. 2023), injury tolerance data for child lumbar loads remain limited.

The findings of this study may not apply to all child anthropometries and CRS. To focus on maximum excursion without interaction with the front seat (which position can vary across interior designs), front-row contact was excluded, so metrics related to contact-induced head injuries were not obtained from scenarios involving hard contact with the head. The seat and interior geometry were developed based on a coach layout; however, the quantitative results may differ depending on factors such as seat stiffness, seatbelt anchorage positions, and seatback geometry. The authors consider the model a reasonable approximation of the interior of this type of vehicle in the absence of a detailed, validated, available coach finite element model. Future studies may implement a seat with more deformable parts to capture the displacement of the d-ring during child-restraint, which may impact excursions and head impact severity if included. Furthermore, a systematic variation of the bus seatbelt anchorage and d-ring geometry (as highlighted by Martínez et al. (2011)) may also be included.

Only two child anthropometries were simulated using a specific booster seat model, so different outcomes may arise with other CRS. Including younger children in either forward-facing or rear-facing CRSs might yield different results. The booster seat was also used only in a nominal child posture. Non-nominal postures, such as slouching, sitting sideways, or leaning forward, and improper routing of the seatbelt may lead to larger excursions, poor seatbelt interaction, and a higher injury risk (Bilston et al. 2007; Bohman et al. 2018). The use of rear and forward-facing CRS with harnesses may avoid some of the mentioned misuses.

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FIGURES

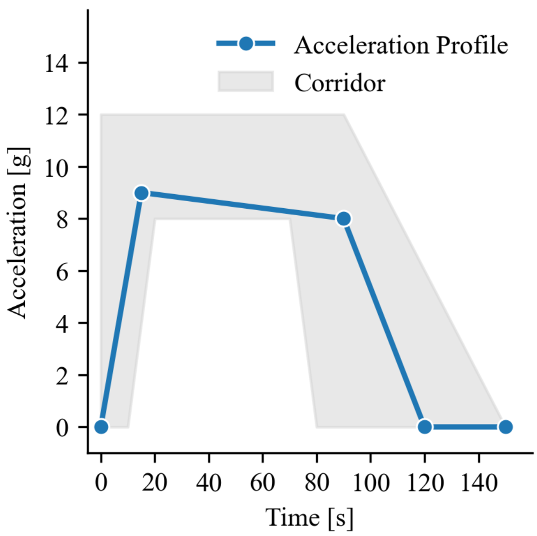

Figure 1. Frontal crash acceleration pulse used in the PIPER HBM simulations.

a)

b)

Figure 2. 3YO and 6YO PIPER HBM models (subfigures a and b, respectively) seated in the bus model in two configurations: 3P seatbelt with no Booster (orange) and with Booster (blue).

a)

b)

Figure 3. 3YO PIPER HBM excursion combined with no Booster (green), Booster (blue), and Booster+ISOFIX (orange) using a 2P seatbelt (top)) and a 3P seatbelt (bottom).

a)

b)

Figure 4. 6YO PIPER HBM excursion combined with no Booster (green), Booster (blue), and Booster+ISOFIX (orange) using a 2P seatbelt (shown at 150 ms) and a 3P seatbelt (shown at 100 ms).

TABLES

Table 1: Simulation matrix used to perform the study.

	3YO	6YO
Unrestrained	No seatbelt	No seatbelt
2P installation	Without Booster	Without Booster
	Booster	Booster
	Booster+ISOFIX	Booster+ISOFIX
3P installation	Without Booster	Without Booster
	Booster	Booster
	Booster+ISOFIX	Booster+ISOFIX

Table 2. Head outcomes for the 3YO occupant. Restrained occupants are shown for 2P and 3P (in bold) seatbelt configurations.

	Unrestrained	Without Booster	Booster	Booster + ISOFIX
Max head excursion [mm]	789	717 / **321**	648 / **205**	615 / **217**
Expected head contact	Yes	Yes / **No**	Yes / **No**	Yes / **No**
Head exceeding 550 mm from Cr seat point	Yes	Yes / **No**	Yes / **No**	Yes / **No**

Table 3. Neck and lumbar spine forces and moments estimated for the 3YO occupant with a 2P and 3P (in bold) seatbelt and different Booster configurations, using Fz/Fx/My following SAE J211 convention.

	Without Booster			Booster			Booster + ISOFIX		
	Fz (kN)	Fx (kN)	My (Nm)	Fz (kN)	Fx (kN)	My (Nm)	Fz (kN)	Fx (kN)	My (Nm)

C1	0.1 / 0.3 / 2.8 **0.2 / 0.3 / 1.1**	0.1 / 0.2 / 2.9 **0.2 / 0.3 / 1.8**	0.1 / 0.3 / 2.7 **0.2 / 0.3 / 1.9**
L1-L2	0.3 / 0.1 / 1.4 **0.1 / 0.2 / 2.5**	0.4 / 0.2 / 1.5 **0.1 / 0.1 / 3.8**	0.5 / 0.2 / 1.5 **0.0 / 0.2 / 2.5**
L2-L3	0.2 / 0.1 / 3.7 **0.1 / 0.1 / 1.2**	0.3 / 0.2 / 5.2 **0.0 / 0.1 / 2.4**	0.4 / 0.3 / 4.4 **0.0 / 0.2 / 2.5**
L3-L4	0.2 / 0.1 / 6.5 **0.1 / 0.2 / 2.7**	0.4 / 0.2 / 8.9 **0.0 / 0.1 / 1.2**	0.4 / 0.2 / 7.4 **0.0 / 0.2 / 2.4**
L4-L5	0.2 / 0.1 / 8.2 **0.1 / 0.2 / 3.4**	0.4 / 0.2 / 11 **0.0 / 0.1 / 0.5**	0.4 / 0.3 / 8.6 **0.0 / 0.2 / 2.1**

Table 4. Head outcomes for the 6YO. Restrained occupants are shown for 2P and 3P (in bold) seatbelt configurations. *Booster+ISOFIX with 2P seatbelt simulation did not reach 150 ms, as it stopped at 105 ms.

	Unrestrained	Without Booster	Booster	Booster + ISOFIX
Max head excursion [mm]	786	757 / **316**	702 / **229**	405* / **239**
Expected head contact	Yes	Yes / **No**	Yes / **No**	Yes* / **No**
Head exceeding 550 mm from Cr seat point	Yes	Yes / **No**	Yes / **No**	Yes* / **No**

Table 5. Neck and lumbar spine forces and moments estimated for the 6YO occupant with a 2P and 3P (in bold) seatbelt and different Booster configurations, using Fz/Fx/My following SAE J211 convention. *Booster+ISOFIX with 2P seatbelt simulation did not reach 150 ms, as it stopped at 105 ms.

<table>
<tr><th></th><th colspan="3">Without Booster</th><th colspan="3">Booster</th><th colspan="3">Booster + ISOFIX</th></tr>
<tr><th></th><th>Fz (kN)</th><th>Fx (kN)</th><th>My (Nm)</th><th>Fz (kN)</th><th>Fx (kN)</th><th>My (Nm)</th><th>Fz (kN)</th><th>Fx (kN)</th><th>My (Nm)</th></tr>
<tr><td>C1</td><td colspan="3">0.1 / 0.3 / 2.1
0.2 / 0.3 / 1.5</td><td colspan="3">0.0 / 0.2 / 1.7
0.3 / 0.4 / 2.9</td><td colspan="3">0.1 / 0.3 / 2.3*
0.2 / 0.4 / 2.8</td></tr>
<tr><td>L1-L2</td><td colspan="3">0.3 / 0.1 / 2.1
0.1 / 0.2 / 2.7</td><td colspan="3">0.3 / 0.2 / 1.9
0.0 / 0.2 / 5.6 N</td><td colspan="3">0.4 / 0.2 / 1.2*
0.0 / 0.2 / 3.2</td></tr>
<tr><td>L2-L3</td><td colspan="3">0.3 / 0.1 / 4.5
0.0 / 0.2 / 2.2</td><td colspan="3">0.2 / 0.3 / 5.1
0.0 / 0.3 / 3.8</td><td colspan="3">0.4 / 0.3 / 5.4*
0.0 / 0.2 / 2.3</td></tr>
<tr><td>L3-L4</td><td colspan="3">0.2 / 0.1 / 8.0
0.1 / 0.2 / 3.5</td><td colspan="3">0.3 / 0.3 / 9.8
0.0 / 0.3 / 1.9</td><td colspan="3">0.4 / 0.3 / 10.2*
0.0 / 0.2 / 1.7</td></tr>
<tr><td>L4-L5</td><td colspan="3">0.2 / 0.1 / 10.2
0.1 / 0.2 / 3.9</td><td colspan="3">0.3 / 0.3 / 12.8
0.0 / 0.3 / 0.8</td><td colspan="3">0.4 / 0.3 / 13.1*
0.0 / 0.2 / 1.0</td></tr>
</table>

APPENDIX

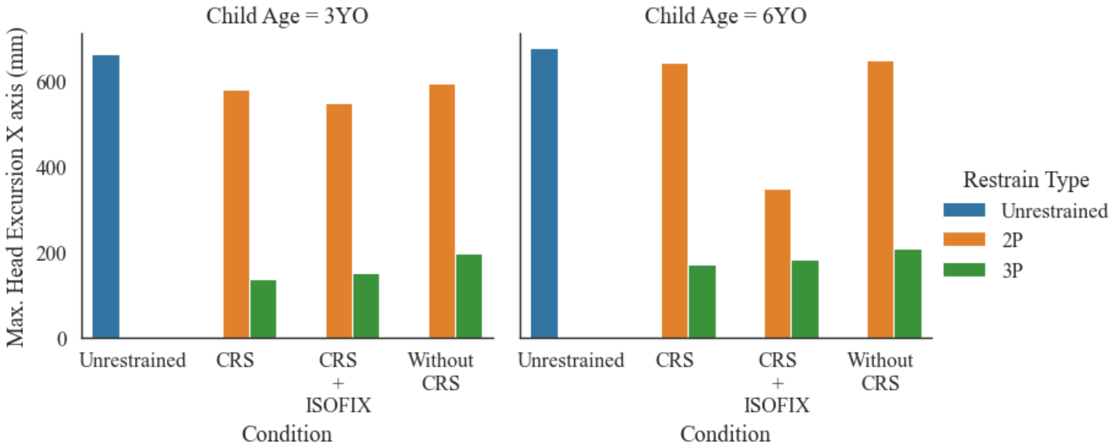

Figure A1. Maximum forward head excursion observed for the different restraint conditions.