Safety Assessment of Aftermarket Devices for Pregnant Occupants and Children: Market Analysis and Sled Testing

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Abstract Aftermarket seat belt-modifying devices, marketed for children and pregnant drivers/passengers have become increasingly prevalent across global online marketplaces. These devices – typically marketed as comfort enhancers or safety-improving accessories – exist outside formal regulatory frameworks governing restraint-system performance, including UNECE and FMVSS standards. Consequently, no independent evaluations are required before such devices reach consumers.

The present study investigates 10 representative aftermarket devices – five targeted at children and five at pregnant occupants – using dynamic sled tests performed with a Q3 3-year-old, a Hybrid III 6-year-old, and a Hybrid III MAMA-2B. Devices tested with the Hybrid III dummies were compared to reference tests. The aim was to determine how these devices influence belt geometry, pretensioner function, occupant kinematics, and biomechanical loading patterns.

None of the devices improved any safety-relevant metric, and several introduced biomechanical conditions associated with increased risk of injury. Child-oriented devices introduced belt slack, elevated the lap belt into the abdomen, and increased forward excursion. Pregnancy-oriented devices frequently disrupted pelvis–belt coupling, generated abdominal loading, and delayed shoulder-belt activation.

The study highlights significant gaps in consumer protection and regulatory oversight, and underscores the need for clearer safety communication, enforcement against misleading marketing claims, and evidence-based guidance for vulnerable occupant groups.

Keywords Aftermarket devices; Child occupants; Restraint systems; Seatbelt; Pregnant occupants

I. INTRODUCTION

The seat belt is the most vital safety feature in a car, cutting the risk of fatal injury by around 50% [1]. For maximum protection, crash forces must be transferred to strong skeletal structures – primarily the pelvis, ribcage, sternum, and clavicle [2]. To provide the intended occupant protection, the seat belt should be positioned in accordance with the vehicle manufacturer's recommendations. The seat belt should be positioned with the lap belt resting low and snug across the hip bones and the shoulder belt running diagonally over the centre of the chest and lying firmly on the clavicle. Proper fit ensures that belt pretensioners, belt load limiters and airbags function as intended. Deviations from ideal seat belt fit can alter force distribution and compromise occupant protection [3].

These biomechanical requirements are particularly critical for children and pregnant occupants. In children, underdeveloped pelvic structures increase the risk of the lap belt riding up over the abdomen, potentially transmitting crash forces to vulnerable soft tissues [4]. While limited slack in a standard seat belt is generally managed by the pretensioner, excessive slack can significantly compromise the restraint system's effectiveness. Additionally, belt misplacement may increase forward excursion or induce torso rotation, further reducing protective performance.

Pregnant occupants face a distinct set of challenges. In late gestation, the enlarged uterus lacks the skeletal protection necessary to dissipate crash forces safely. Proper seat belt placement – diagonal belt on the shoulder and snugly across the chest, lap belt below the belly and snugly across the hips [5] – is therefore essential to prevent direct loading of the uterus and placenta. Incorrect belt positioning has been associated with adverse maternal and foetal outcomes, including placental abruption and uterine injury [6].

Despite the heightened sensitivity of these groups to belt geometry, aftermarket devices that alter seat belt routing and/or safety performance have proliferated across online marketplaces. These accessories are often

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marketed as comfort aids or safety enhancements. The design typically involves repositioning the belt, limiting its natural retraction, or introducing additional interfaces between the belt and the occupant's body. Consumers may mistakenly interpret these devices as certified or medically endorsed, although they are not required to comply with any recognised safety standard for restraint performance. A recent questionnaire study in Sweden, comprising responses from 2,034 women who were pregnant or had previously been pregnant, found that 16% reported using an aftermarket device [7].

The current regulatory framework for vehicle safety comprises international automotive standards – such as UNECE Regulations 14, 16, 44 and 129, together with FMVSS 208 and 209 in the United States – which govern the performance, geometry, anchorage strength and crashworthiness of restraint components integrated into vehicles by manufacturers. These regulations mandate dynamic testing using validated anthropomorphic test devices (ATDs) and impose strict criteria for injury metrics [8-9]. In addition, national user regulations apply. In Sweden, for example, the use of child restraint systems (CRSs) is legally restricted to devices type-approved in accordance with UN Regulation No. 44 or No. 129, and correct seat belt routing and tension are explicitly prescribed [10]. However, the scope of these regulatory frameworks is limited to original equipment manufacturer (OEM) systems and certified CRSs. Consumer-added accessories, including those that reposition or constrain the belt, fall entirely outside these regulatory frameworks. Within the European Union, only CRSs type-approved in accordance with UN Regulation No. 129 are permitted to be placed on the market.

This regulatory gap has significant implications. Unlike vehicle-integrated restraint components, aftermarket belt-modifying devices are not subject to dynamic sled testing, structural integrity assessments, or material validation. Manufacturers are therefore able to market devices that fundamentally alter belt mechanics without demonstrating their safety performance. As a result, devices that may compromise the biomechanical effectiveness of restraint systems [11-12] are freely available.

The present study examines 10 representative aftermarket devices – five designed for children and five for pregnant occupants – using dynamic sled tests conducted with three different ATDs; Q3 3-year-old (3yo), a Hybrid III 6-year-old (6yo), and a Hybrid III MAMA-2B (a 5th percentile female ATD equipped with a validated pregnancy insert). The main objective of this work was to examine whether the investigated aftermarket devices have the potential to improve, or adversely affect, safety for children and pregnant women. Specifically, the study aimed to determine how these devices influence belt geometry, pretensioner performance, occupant kinematics, and biomechanical loading patterns in comparison with correct restraint use in accordance with the recommendations.

II. METHODS

The methodological approach was designed to reflect how aftermarket devices are intended to be used, while maintaining the experimental control required to evaluate their biomechanical consequences. The present paper builds on two technical reports developed for the Swedish context, and Swedish child restraint recommendations were therefore used as a point of reference. The work began with a review of major online retail platforms with broad international availability, aimed at identifying commonly available aftermarket devices for children and pregnant occupants. Conducted over a relatively extended period prior to product acquisition, the review revealed a broad and largely unregulated market of devices intended to modify belt routing or contact points.

Based on this review, ten aftermarket devices were selected to illustrate a range of different functional concepts; five designed for children and five intended for pregnant users. The devices were purchased on websites accessible across the world. One acquired device, a seatbelt extender, was omitted from the test series due to the potential risk of damaging the ATD's pregnant abdomen (Fig. A1 in Appendix).

All testing was carried out using standard vehicle seats to ensure that the baseline performance accurately represented real-world restraint-system behaviour. The child-oriented devices were evaluated in the outboard rear seating positions of a Volvo V60 (model year 2012), together with a seat belt retractor featuring pyrotechnic pretensioning and a progressive load-limiting function. The pregnancy-oriented devices were assessed in the driver's seat of a Volvo V70 (model years 2008–2016), also fitted with a seat belt retractor incorporating pretensioning and a load-limiting function. The pretensioners were triggered at T=12 ms.

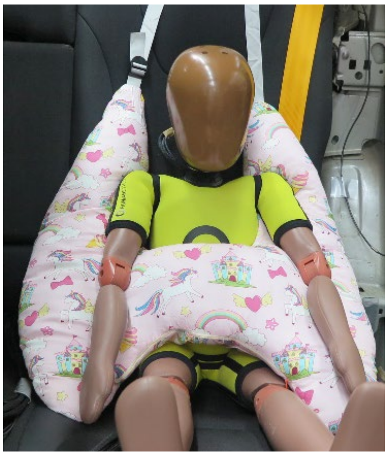
Three ATDs were selected to represent key occupant categories. The Q3 3yo was used to evaluate three of the child-oriented devices (Fig. 1(a)–(c)), while the Hybrid III 6yo was used to test the remaining two devices (Fig. 2(b)–(c)). A Hybrid III 5th percentile female ATD equipped with the MAMA-2B pregnancy insert [13] was used to assess the five aftermarket devices intended for pregnant occupants (Fig. 3(b)–(f)).

In addition, two reference tests were conducted based on the Swedish recommendations for child [14] and pregnant [15] occupants. One was conducted with the Hybrid III 6yo seated on a booster cushion (Reference 1, Fig. 2(a)), and one using the Hybrid III MAMA-2B with the unmodified three-point belt configuration (Reference 2, Fig. 3(a)). It was decided not to conduct a reference test with the Q3 3yo, as children are recommended to travel rear-facing until at least 4–5 years of age according to the Swedish recommendations [14], whereas the three tested products were intended for forward-facing use.

To reflect real-world conditions as closely as possible, all installations followed the instructions supplied with each aftermarket device. Where instructions were incomplete or ambiguous – which was generally the case – the installation was performed according to the most plausible interpretation that a typical consumer might apply, based on product images and descriptions. This approach ensured that performance outcomes were representative of consumer use rather than laboratory optimisation. ATDs were placed in neutral seating postures without manual adjustment to improve belt fit or device alignment.

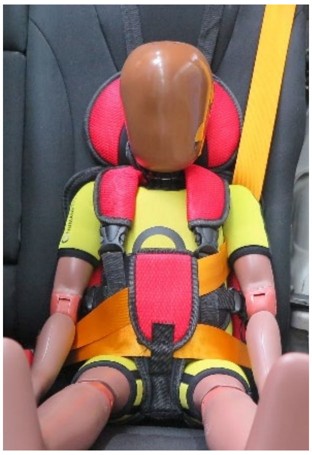
Dynamic testing was conducted on a HYGE sled using the Euro NCAP full-width rigid-barrier 50 km/h crash pulse. This pulse generates a rapid onset of acceleration and a peak of approximately 30 g, conditions that are particularly sensitive to belt slack, routing deviations, and timing of pretensioner activation.

(a) Product A.



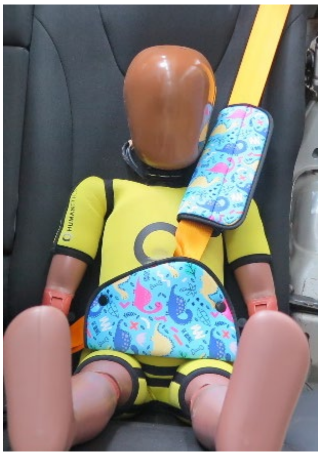
Cushion attached with a strap around the head restraint. The diagonal and lap belt threaded into guide on the back of the cushion. Diagonal belt positioned under the arm.

(b) Product B.



Harness attached with straps around the seat back. The diagonal and lap belt threaded into a double-folded flap in front of the waist. Diagonal belt positioned under the arm.

(c) Product C.



Diagonal and lap belt threaded through double-folded padding held together by stitching and two press studs. Padding fastened around the diagonal belt using Velcro.

Fig. 1. Child-oriented devices tested with the Q3 3yo.

(a) Reference 1.

The diagonal and lap belt run underneath the seat belt guides of a booster cushion.

(b) Product D.

Diagonal and lap belt connected by a strap secured with clips.

(c) Product E.

Diagonal and lap belt joined with a metal buckle.

Fig. 2. Child-oriented devices tested with the Hybrid III 6yo.

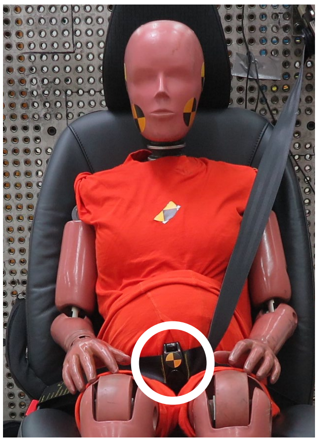
(a) Reference 2.

Seat belt only.

(b) Product F (diagonal belt).

Belt extraction: 30 mm. Clamp at the shoulder D-loop preventing belt retraction.

(c) Product G (dual belt).



Belt extraction: 170 mm. Clamp holding the lap and diagonal belts together.

(d) Product H.

Belt extraction: 0 mm. The lap belt is held by a double-folded flap attached to a ‘seat pad’ which was attached to the seat back by a strap.

(e) Product I.

Belt extraction: 250 mm. The lap belt is held by a plastic hook attached to the seat base.

(f) Product J.

Belt extraction: 260 mm. The lap belt is held by a metal buckle attached to the seat base.

Fig. 3. Pregnancy-oriented devices tested with the Hybrid III MAMA-2B ATD. *Note:* Products F and G are the same but used in different ways.

The primary analyse method for all ATDs was based on evaluation of the recorded high-speed video captured at 1,000 frames per second. For aftermarket devices tested with the Q3 3yo, the evaluation relied solely on this video analysis. For the HIII 6yo and HIII MAMA-2B, the video analysis was complemented by additional instrumentation. For the HIII 6yo, this included triaxial accelerometers located in the head, chest, and pelvis, uniaxial accelerometers in the upper and lower spine, and triaxial neck load cells in the upper and lower neck. Pelvic excursion of the HIII MAMA-2B and head excursion of the HIII 6-year-old was obtained through video analysis using TEMA software. Data were filtered in accordance with SAE J211 protocols. Video footage was time-synchronised with sensor outputs to allow detailed analysis of belt trajectory, torso kinematics, pelvis displacement, and visual indicators of submarining.

As the main objective of this work was to examine whether the investigated aftermarket devices have the potential to improve, or adversely affect, safety for children and pregnant women, comparing sensor outputs from ATDs does not provide a meaningful or reliable basis for addressing this question. At present, there is no established or validated test method specifically developed for this type of aftermarket devices. Furthermore, the dummy measurements cannot be directly related to established injury thresholds, and comparisons with the reference condition are not straightforward. The intention of the test series was therefore not to assess changes in injury risk based on dummy sensor data, but rather to investigate whether the introduction of these devices could negatively influence the overall dynamic performance. Thus, findings were interpreted in a biomechanical rather than statistical framework, reflecting the deterministic nature of restraint-system behaviour when geometry and routing are altered.

III. RESULTS

The dynamic sled tests revealed a consistent pattern across the aftermarket devices evaluated: none improved any safety-relevant metric, and the majority introduced biomechanical conditions strongly associated with severe injury in real-world crashes. Although the mechanisms of degradation differed between child-oriented and pregnancy-oriented devices, common underlying mechanisms – namely slack induction, misrouting, disrupted belt–body coupling, or impaired pretensioner engagement – were evident across most configurations.

Observations from the tests with the Q3 3yo

In the test involving *Product A*, the diagonal belt was positioned beneath the Q3's arm, resulting in the absence of any restraint to control the upper torso during the crash event. Consequently, the torso folds over the belt and moves forward relative to the seat (Fig. 4). At 133 ms, the head gets in contact with the legs, while the diagonal belt exerts an upward load on the abdominal region. The torso then continues rearwards in an oblique motion, coming to rest on the ATD's right side. In a real-world crash, the risk of more severe injury in the torso/abdomen region would likely be increased under these circumstances. The manufacturer's claim that the device does not affect the performance of the vehicle's seatbelt system is therefore demonstrably incorrect.

Fig. 4. Product A – side view at 94 ms.

In the test involving *Product B*, the diagonal belt is again positioned beneath the Q3's arm, but in this case the ATD is also equipped with a harness secured with webbing around the seat back. As shown in Fig. 5, Product B does not provide sufficient restraint of the upper torso during the crash event, leaving it effectively unsupported. As a result, the torso folds over the belt and moves forward relative to the vehicle. At 115 ms, the head strikes the legs, while the diagonal belt imposes an upward load on the abdominal region. The torso subsequently moves rearwards in an oblique trajectory and comes to rest on the dummy's right side. In a real-world crash, the risk of more severe injury in the torso/abdomen region would likely be increased under these circumstances.

Fig. 5. Product B – side view at 90 ms.

In the test with *Product C*, slack is introduced into the seat belt system, causing the diagonal belt to be pulled upwards during the pretensioning phase. At 24 ms, Product C is fully tensioned between the diagonal and lap belts, leading to the onset of seam failure. By 45 ms, one of the press-stud fasteners is also torn open (Fig. 6), resulting in the diagonal belt separating from the lap belt. During pretensioning, Product C additionally pulls the lap belt upwards, causing the child's right hip to slide underneath the belt. In a real-world crash, the risk of more severe injury in the abdomen region would likely be increased under these circumstances.

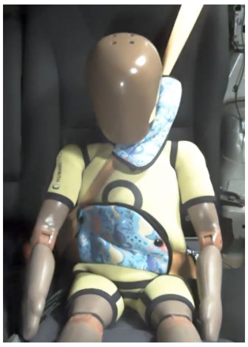


Fig. 6. Product C – front view at 45 ms.

Observations from the tests with the Hybrid III 6yo

In the test involving *Product D*, which is intended to function as a replacement for a booster cushion (or equivalent device), the device was compared with the reference configuration (Reference 1). The results indicate that Product D produced an earlier deceleration of the upper torso compared to the reference condition. This effect is clearly illustrated in the high-speed video recordings, which show reduced head excursion when using Product D, with a difference of approximately 8.7 cm relative to the reference test (Fig. 7).

The increased stiffness of the belt system resulted in substantially higher neck loads in both the upper and lower neck regions (+32% and +70%, respectively) (Table A1 in Appendix). Moreover, Product D generated 7–19% higher accelerations in the upper body (chest, lower/upper spine, and head), while the hip acceleration was 20% less than in the reference condition. The Head Injury Criterion (HIC15) was also elevated when using Product D (+41%).

Overall, Product D increased loading on the upper torso, neck and head, while reducing loading at the hip.

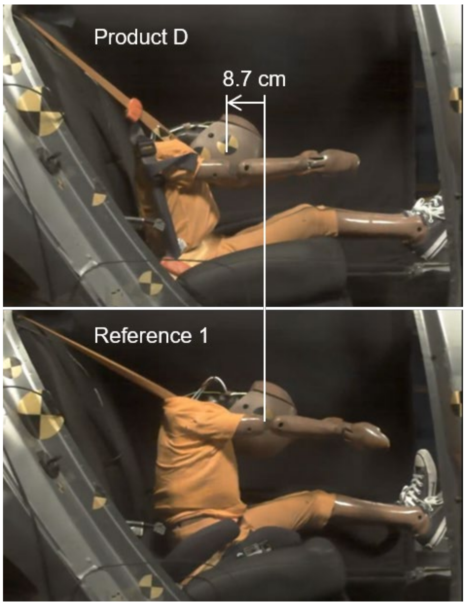


Fig. 7. Product D (top) compared with the reference test with a booster cushion (bottom) at the time of maximum head excursion.

In the test involving *Product E*, the device was displaced upwards during the belt pretensioning phase and failed after 30 ms. In addition, Product E pulled the lap belt upwards during pretensioning, resulting in pronounced intrusion into the abdominal region (Fig. 8). In a real-world crash, the risk of more severe injury in the torso/abdomen region would likely be increased under these circumstances.

It should also be noted that the product brochure indicates that this device is intended for use by adults as well. Given that the device failed under the loading conditions imposed by a 23 kg crash test dummy, it is unlikely to withstand the substantially higher loads generated by an adult occupant.

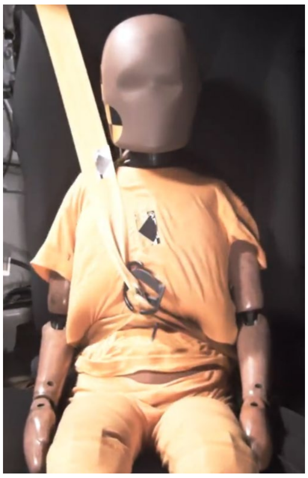


Fig. 8. Product E – frontal view at 32 ms.

Observations from the tests with the Hybrid III MAMA-2B

A reference test – Reference 2 – was conducted without any aftermarket device (Fig. 9). Video analysis showed a hip excursion of 155 mm (mean value for the left and right sides). Throughout the crash event, the belt remained positioned below the abdomen, and the ATD moved straight into the seatbelt without any tendency to rotate.

In the test involving *Product F* (diagonal belt clamp), two approaches were considered: introducing a large slack, which the pretensioner would have been unable to retract; or a small slack, which would not have sufficiently challenged the product. Following discussions within the project group, a slack of 30 mm was selected (Fig. 2, Fig. 10), i.e. substantially less than the pretensioner stroke of approximately 140–163 mm.

During the test, Product F detached from the webbing as early as 18 ms due to the pretensioning. Consequently, nearly all the introduced slack was eliminated. Despite this, some differences from the reference test were observed. Notably, the diagonal belt was positioned further out on the shoulder, causing the dummy to exhibit a tendency to rotate around the belt. Hip excursion was also slightly greater at 175 mm, compared with 155 mm in the reference test (Fig. 15).

A greater initial slack, or a clip that remained more firmly secured (i.e. did not release during pretensioning), would likely have altered the resulting kinematic and loading characteristics.

During the test involving *Product G* (dual belt clamp), the clamp detached considerably later (48 ms) than observed for Product F (18 ms), leaving a substantial amount of slack in the belt throughout the entire crash event. This resulted in the diagonal belt slipping off the shoulder and becoming positioned directly across the abdomen (Fig. 11), a configuration associated with a potentially serious risk of abdominal injury.

The downward displacement of the belt from the shoulder also caused the upper torso to rotate over the diagonal belt. Submarining of the right side of the pelvis was observed, and the pelvis excursion increased markedly to 234 mm (Fig. 15).

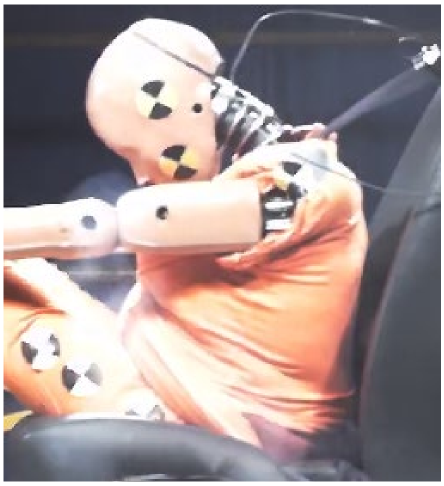


Fig. 9. Side view of the reference test without comfort product.

Fig. 10. Detail view of Product F (diagonal belt), which was secured around the diagonal belt in direct contact with the D-loop.

Fig. 11. Front view of the test with Product G (dual belt clamp).

In the test involving *Product H*, it was observed that the double-folded flap positioned the lap belt slightly higher (Fig. 2(d)) than in the reference test (Fig. 2(a)). Furthermore, hip excursion was slightly greater, at 172 mm (Fig. 12(a)), compared with 155 mm in the reference test (Fig. 15).

The seams securing the webbing to the 'seat pad' on both the left and right sides tore, detaching Product H from the seat base (Fig. 12(b)). This indicates that Product H likely had minimal influence on the function of the seat belt system.

Throughout the crash event, the belt remained positioned below the abdomen, and the dummy moved straight into the seat without any tendency to rotate.

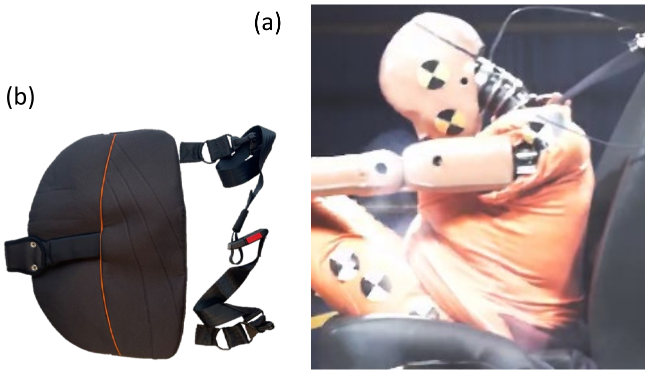


Fig. 12. (a) Side view of the test with Product H at maximum pelvis excursion. (b) Product H after test showing the separation of the straps from the 'seat pad'.

Product I underwent substantial deformation (Fig. 13(b)), and the locking mechanism of the strap securing it to the seat ceased to function. As a result, the hook rotated upwards towards the abdomen, and the pelvis excursion increased markedly to 253 mm (as indicated with a red arrow in Fig. 13(a)) compared with 155 mm in the reference test (Fig. 9, Fig. 15). Such an outcome is unfavourable from a safety perspective, as minimising pelvis excursion is essential to prevent belly interaction with the steering wheel. The lap belt remained positioned below the abdomen throughout the test.

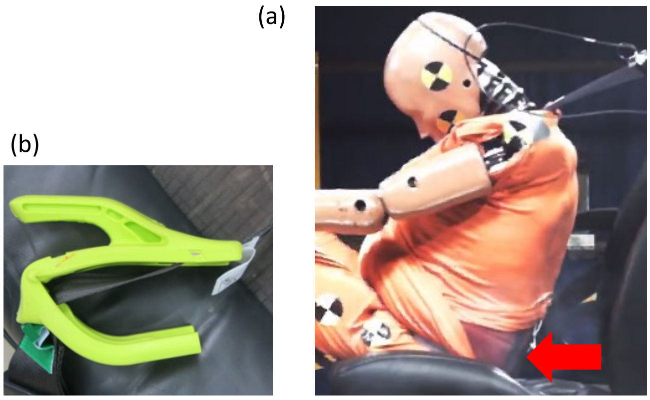


Fig. 13. (a) Side view of the test with Product I at maximum pelvis excursion. (b) Visible deformation of Product I after test.

During the test involving *Product J*, the metal buckle underwent substantial deformation (Fig. 14(b)) and rotated upwards towards the abdomen. At 49 ms, the lap belt fully detached from the buckle. This resulted in a markedly increased pelvis excursion of 306 mm (as indicated with a red arrow in Fig. 14(a)) compared with 155 mm in the reference test (Fig. 9, Fig. 15). Such an outcome is unfavourable from a safety perspective, as minimising pelvis excursion is essential to prevent belly interaction with the steering wheel. During the rebound phase, the dummy's head was pressed upward, from below, into the bottom of the head restraint.

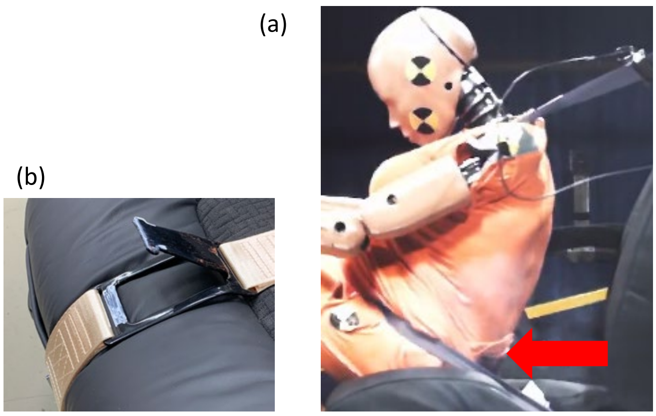


Fig. 14. (a) Side view of the test with Product J at maximum pelvis excursion. (b) Visible deformation of Product J after test.

As can be seen in Fig. 15, all tested pregnancy-oriented devices had greater pelvis excursions compared to Reference 2 (only seat belt).

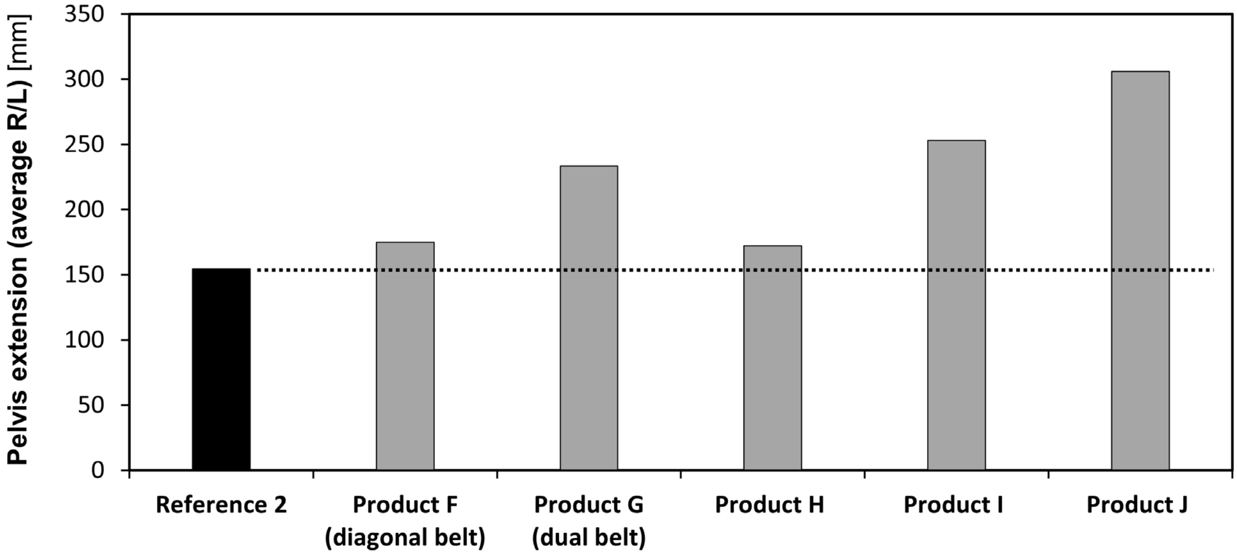


Fig. 15. Pelvis excursion for the tested pregnancy-oriented devices (grey bars) in comparison to the reference test (black bar).

IV. DISCUSSION

The present study demonstrates that aftermarket belt-modifying devices – regardless of their intended user group or mechanical concept – introduce predictable, systematic, and potentially harmful deviations in restraint system performance. Although the devices varied widely in construction, attachment method and marketed purpose, the underlying biomechanical consequences were strikingly consistent. Across both child and pregnancy configurations, most products altered belt geometry, generated slack, impeded pretensioner function, or disrupted belt–body coupling in ways that degraded the occupant's protective envelope. Importantly, the findings confirm established restraint design and biomechanical guidelines, and show that adverse deviations in belt geometry arise not only due to misuse, but also when the devices are used in accordance with the manufacturers' own product images, descriptions and/or instructions.

A key observation is that the aftermarket devices, to various extents, undermined the foundational principle of modern seat belt design, i.e. early and sustained engagement of skeletal structures capable of tolerating crash-induced loads. For child occupants, several devices elevated the lap belt into the abdomen or routed the shoulder belt beneath the arm, allowing forward motion of the torso without the stabilising effect of the thorax and pelvis. The findings for Products A and B, where the torso folded over the belt and the head contacted the lower extremities (Fig. 4 and Fig. 5), demonstrate the severity of these deviations

Other devices, such as Product D, altered system stiffness rather than routing (Fig. 7). By reducing belt compliance, the device caused earlier torso deceleration and markedly elevated neck loads and HIC value. Although lower head excursion might appear beneficial, the associated increases in neck tension and upper torso acceleration indicate a shift of load transfer to less injury tolerant anatomical regions. This highlights an important point for consumer perception: changes that look 'tighter' or 'more controlled' in static or low speed conditions may actually indicate an unfavourable redistribution of crash forces at real-world speeds.

Devices that failed structurally under load (Products E, I and J) raise further concerns. Structural failure occurred within the first 50 ms of the event, i.e. when pretensioners and load limiters are designed to manage peak belt forces. For Product E, the metal buckle failed under loads generated by a 23 kg ATD (Fig. 8), suggesting a profound mismatch between product strength and foreseeable loading conditions. For pregnancy-oriented devices, structural deformation of hooks (Fig. 13(b)) and buckles (Fig. 14(b)) was associated with substantial increases in pelvis excursion, in some cases doubling the displacement observed in the reference test. For a pregnant driver, the consequences of such uncontrolled motion are particularly severe. If the pelvis isn't properly restrained, the enlarged uterus can move forward enough to collide with the steering wheel. A longitudinal study, measuring belly-to-steering-wheel distance in three pregnant drivers, reported that by the third trimester one participant had less than 12 cm of clearance; they cautioned that even a moderate forward excursion could eliminate this gap and result in abdominal contact with the steering wheel in a crash [16]. According to recommendations by for example Transport Canada [18] the distance should be at least 25 cm (10 inches) between the steering wheel hub and the thorax or abdomen. Blunt force to a pregnant abdomen is known to cause placental abruptions, uterine ruptures, and direct foetal injury [17]. Furthermore, if interactions with frontal airbags and airbag activation would be considered the clearance is even more crucial.

The pregnancy-specific findings further underline the incompatibility between these devices and the biomechanical realities of late gestation restraint. Proper belt-to-pelvis coupling is essential to ensure that the large uterus is not subjected to rapid loading. Yet pregnancy-oriented aftermarket devices introduced measurable pre-crash gaps between the belt and the pelvis, delayed belt engagement, or prevented the belt from tightening effectively during pretensioning. Devices that appeared to improve belt comfort or stability in static conditions (e.g. clamps or repositioners that hold the belt 'downwards', Figs 11, 13 and 14) consistently impeded dynamic belt function.

From a regulatory perspective, the findings highlight a significant gap in consumer protection. Vehicles and certified CRSs undergo rigorous testing to ensure that belt geometry and load paths are safe across a wide range of occupants. Yet manufacturers of belt-routing accessories can market products that directly interfere with these systems without any requirement to demonstrate safety performance. As the devices are positioned as comfort or convenience items, they evade both automotive regulatory frameworks and medical device oversight. This creates a misleading environment in which consumers – particularly parents and pregnant women seeking to protect vulnerable occupants – may purchase products that actually increase risk.

Among the aftermarket devices tested the information for customers regarding recommended age, weight, and height was very limited. There is a need for improved customer guidance.

The results of this study build a compelling case f or stronger regulatory scrutiny, clearer consumer guidance, and enforcement mechanisms to ensure that marketing claims do not misrepresent safety benefits. At a minimum, safety communication should emphasise that unmodified use of the vehicle's certified restraint system, or by using an approved CRS, remains the most effective protection for both children and pregnant occupants. More broadly, the study provides biomechanical evidence that unapproved aftermarket devices, regardless of design, introduce deterministic failures in restraint performance. These failures are not artefacts of testing but inherent consequences of attempting to modify a tightly engineered safety system with unvalidated add-on components.

A limitation of the present study is that no forward-facing CRS reference test was conducted with the Q3 3yo. Although forward facing restraint configurations for 3-year-old children are still used in many countries, the study was intentionally designed to reflect the Swedish child occupant safety context, where rear-facing travel is strongly recommended up to at least 4-5 years of age. Recent Swedish in-depth analyses of fatal child car occupant crashes have shown that a substantial proportion of fatalities among children aged 0–3 years occurred when forward facing CRS or other non-recommended restraint solutions were used, and that a large share of these outcomes were assessed as potentially preventable with rear-facing CRS use [19-20]. This context should be considered when interpreting the study results for regions with child restraint practices that differ from those in Sweden.

There is no established test method for the aftermarket devices included. Thus, these aftermarket devices are sold without passing any regulation. The analysis in this study was a first attempt to see if these devices have a positive or negative influence on the safety performance. A more thorough analysis and development of a test procedure for this kind of aftermarket devices is recommended. Given the results of this study, further research is highly recommended to investigate how they affect safety, but also to consider whether such aftermarket devices should be allowed to be marketed without any approval.

V. CONCLUSION

This study provides comprehensive biomechanical evidence that aftermarket belt-modifying devices designed for children and pregnant occupants degrade restraint-system performance in critical ways. Across 10 aftermarket devices tested, none provided any safety benefits; instead, most devices introduced mechanisms of injury risk.

The results underscore that the safest configuration for both children and pregnant occupants is correct use of child restraints and/or the three-point belt originally installed by the vehicle manufacturer with no modifications. The findings also reveal a pressing need for improved safety communication, stronger regulatory oversight and public-health guidance discouraging the use of untested restraint accessories. Without such measures, vulnerable occupant groups will remain exposed to unnecessary risk from aftermarket devices that promise comfort or convenience but undermine fundamental protective mechanisms.

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As part of the manuscript preparation process, AI-based tools were used mainly to translate and consolidate two Swedish-language technical reports into an initial English draft. The manuscript was subsequently extensively revised, restructured, and rewritten by the authors.

VII. REFERENCES

[1] Kahane, C. J. (2015) Lives Saved by Vehicle Safety Technologies and Associated Federal Motor Vehicle Safety Standards, 1960–2012 (Report No. DOT HS 812 069). National Highway Traffic Safety Administration: Washington, DC, USA.

[2] Kent, R. W., Forman, J. (2015) Restraint System Biomechanics. In: Yoganandan, N., Nahum, A., Melvin, J. (eds), *Accidental Injury*. *Springer*, New York, NY, USA. https://doi.org/10.1007/978-1-4939-1732-7_5

[3] Siegmund, G. P., Chimich, D. D., Heinrichs, B. E., DeMarco, A. L., Brault, J. R. (2005). Variations in Occupant Response with Seat Belt Slack and Anchor Location During Moderate Frontal Impacts. Traffic Injury Prevention, 6(1), 38-43. doi:10.1080/15389580590903159

[4] Szadkowski, M. A., Bolte, R. G. (2017) Seatbelt Syndrome in Children. Pediatric Emergency Care, February 33(2): pp. 120–125. doi: 10.1097/PEC.0000000000001027.

[5] NHTSA (2025) Seat belt recommendations for pregnant drivers and passengers. (Accessed 20-02-2026.)

[6] Tanaka, K., Motozawa, Y., *et al*. (2022) Severity of placental abruption in restrained pregnant vehicle drivers: Correct seat belt use confirmed by finite element model analysis. *International Journal of Environmental Research and Public Health*, **19**(21): 13905. https://doi.org/10.3390/ijerph192113905.

[7] Carlsson, A., Stigson, H. (2021) Gravidas bältesanvändning - Enkätstudie. Report (in Swedish), Skyltfonden TRV 2019/28181, the Swedish Transport Administration (Trafikverket), Borlänge, Sverige.

[8] UNECE (2018) Regulation No. 16 of the Economic Commission for Europe of the United Nations (UNECE) — Uniform provisions concerning the approval of: I. Safety-belts, restraint systems, child restraint systems and ISOFIX child restraint systems for occupants of power-driven vehicles; II. Vehicles equipped with safety-belts, safety-belt reminders, restraint systems, child restraint systems, ISOFIX child restraint systems and i-Size child restraint systems [2018/629]. https://eur-lex.europa.eu/eli/reg/2018/629/oj/eng. (Accessed 01-04-2026.)

[9] FMVSS (2020) Federal Motor Vehicle Safety Standard No. 208: Occupant Crash Protection. U.S. Department of Transportation. https://web.archive.org/web/20050111234652/http://www.nhtsa.gov/cars/rules/import/FMVSS/#SN208. (Accessed 23-02-2026.)

[10] The Swedish Transport Agency (2014) Transportstyrelsens föreskrifter och allmänna råd) om användning av bilbälten och av särskida skyddsanordningar för barn (TSFS 2014:52) (in Swedish). (Accessed 01-04-2026.)

[11] Takeda, A., Kuwahara, A., *et al*. (2022) Correct use of a conventional lap-and-shoulder seatbelt is safest for pregnant rear-seat passengers: Proposal for additional safety measures. Applied Sciences, **12**: 8776. https://doi.org/ 10.3390/app12178776. (Accessed 23-02-2026.)

[12] ADAC (2023) Was taugen Schwangerschaftsgurte wirklich? Schwangerengurt im Test. https://www.adac.de (Accessed 04-03-2026.)

[13] Rupp, J. D., Shneider, L. W., *et al*. (2001) Development and Test of a Prototype Pregnant Abdomen for the Small-Female Hybrid III ATD. *Proceedings of the 45th Stapp Car Crash Conference*, 2024, Ohio, USA.

[14] NTF (2017) Svenska rekommendationer för barn i bil (in Swedish). (Accessed 20-02-2026).

[15] NTF (2025) Så använder du säkerhetsbältet under graviditeten (in Swedish). (Accessed 04-03-2026.)

[16] Tsuchikawa, S., Oe, Y., Tateoka, Y., Hitosugi, M. (2024) Clearance between the abdomen and the steering wheel of a motor vehicle during the pregnancy—Longitudinal evaluation on the driver's seat. *Journal of the Japanese Council of Traffic Science*, **24**(1), pp. 43–50. https://doi.org/10.24597/jcts.24.1_43.
[17] Petrone, P., Jiménez-Morillas, P., Axelrad, A., Marini, C. P. (2019) Traumatic injuries to the pregnant patient: A critical literature review. *European Journal of Trauma and Emergency Surgery*, **45**(3): pp. 383–392. https://doi.org/10.1007/s00068-017-0839-x.
[18] TransportCanada (2013) Air Bag Deactivation – Reductin the Risk. (https://tc.canada.ca/en/road-transportation/publications/air-bag-deactivation/reducing-risk, (Accessed 03-06-2026)
[19] K Klingegård M, Kullgren A, Stigson H, Ydenius A, Carlsson A, Bohman K, Stockman I, Jakobsson L, Fredriksson R (2025) Child Restraint System (CRS) usage in fatal car crashes in Sweden and the potential of rear-facing CRS to influence injury outcomes. Proc. of the Protection of Children in Cars Conference, 8–10 December 2025, Munich (Germany); pp. 1–15.
[20] Bohman K, Carlsson A, Klingegård M, Stockman I, Jakobsson L, Fredriksson R (2026) A review of all child car occupant fatalities in Sweden from 1992 to 2024. Paper Number 26-216. Proc. of the 28th International Technical Conference on the Enhanced Safety of Vehicles (ESV); May 12–15, 2026, Toronto (Canada).

VIII. APPENDIX

One of the acquired products, a seat belt extender, was omitted from the test series because of the potential risk of damaging the crash test dummy's pregnant abdomen (Fig. A1).

Fig. A1. Belt extender (38.5 cm) used by a mid-sized (164 cm) pregnant woman. Photo by Anna Carlsson.

Table A1. Peak values for Product D and Reference 1.

Measured variable	Direction	Body part	Product A	Reference 1	Product A rel. to Reference 1
Acceleration [g]	X	Lower Spine	-41	-37	11%
		Upper Spine	-37	-31	19%
	Resultant	Pelvis	40	50	-20%
		Chest	39	34	12%
		Head	52	48	7%
HIC15	-	-	258	184	41%
Force [N]	Resultant	Upper Neck	1,928	1,458	32%
		Lower Neck	1,442	849	70%