Front passenger airbag benefits for restrained forward-facing children

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Abstract This study investigates whether the front passenger airbag disabling strategy, developed based on first-generation airbags, is valid for modern airbag designs and restrained forward-facing children from three-year-old (3YO) size. In total, 19 different frontal impact situations were evaluated, comparing with and without airbag activation, using one vehicle model. Restrained child crash test dummies (3YO, 6YO, 10YO), of varied seat positions, booster types, crash pulses and sitting postures (up-right and forward leaning), were tested in sled tests representative of a modern airbag and seatbelt technology. In addition, some typical misuse cases were evaluated.

To different extents, all 19 situations tested demonstrated relative positive, or comparable, effect for activated airbag compared to no airbag. The influence of the airbag was relatively more pronounced in the more forward seat adjustment positions. In the misuse situations, it was clearly more robust using the airbag to help protect the child. Based on the results, Volvo Cars is revising its recommendations for restrained forward facing children travelling in car models with front passenger airbag designs as tested in this study. For these specific car models it is revised to recommend that the airbag should be Enabled for all forward-facing restrained child occupants (as for adults), while kept Disabled for all rearward-facing children.

Keywords Airbag disabling strategies, child airbag interaction, child front-seat occupant, Q-dummies, sled tests.

I. INTRODUCTION

Front passenger airbags have developed significantly since their introduction in the late 1980s. Most requirements and recommendations regarding passenger airbags and children are based on first-generation passenger airbags introduced in the late 1980s/early 1990s. Real world data at that time highlighted the incidences of child fatalities in relation to front passenger airbags [1-3]. Based on this, different recommendations in different parts of the world came into effect. In some countries, children were prohibited in the front seat. In other countries, recommendations requested the passenger airbag to be switched off for children, with different limits on stature or age in different countries. In Sweden, the vehicle industry, together with other stakeholders, signed an agreement in 2006 urging front passenger airbag switch-off (manually by switch or at a workshop) to facilitate the use of the front passenger seat by children. The agreement stated that airbag switch-off was required for children up to 140 cm.

Passenger airbag technologies have evolved over the years, providing, for example, better balanced inflators and advanced foldings with improved positioning behaviour of the airbag. Overall, a modern airbag exhibits a much different behaviour than the first-generation airbags. Specifically, the FMVSS208 *Frontal Occupant Protection* update in 2002 [4] paved the way towards the important features of improving occupant and airbag interaction.

In addition, seatbelt technology developments and airbag developments are working together as an integrated safety system. All front-seat passenger regulatory and consumer information testing includes deployment of front passenger airbags. No standardised testing involves front-seat passenger evaluation using seatbelt only. Hence, the developments of seatbelt technology are not obviously controlled for the protection of occupants occupying the front passenger seat with the airbag disabled

With the aim of providing scientific evidence regarding low-risk or suppression options for passenger airbags when forward-facing children are seated in the front seat, Menon *et al.* [5] performed real-world surveillance

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studies, sled tests and simulation series on restrained children in frontal crashes. Although an extensive study, they concluded that more investigation would have to be conducted before firm recommendations could be made. Although some of their tests suggested a possible beneficial role of the airbag for certain crash scenarios involving children, it is not clear what type of airbag design was used in that testing. The real-world data showed that restrained children were not at as high a fatality risk as previously reported for predominantly unrestrained children and that the injuries to which restrained children were exposed by airbags were mostly not life-threating [5]. A large variation among vehicle types was seen, with particular concerns for SUVs and passenger vans.

Taking into account the disabling/enabling of front passenger airbags, two overall types of misuse can occur: transportation of a child while the airbag is enabled; and transportation of an adult while the airbag is disabled. Using observations and interviews (internet questionnaires), Johannsen *et al*. [6] found misuse of both types in real-world situations.

Child recommendations, strategies and legislation are based on the first-generation airbag. The objective of this study is to investigate whether the disabling strategy still apply for a specific modern front passenger airbag design. Specifically, the focus here is on restrained forward-facing children from the size of a 3YO. Smaller children are optimally protected in rearward-facing child seats. A front passenger airbag will likely not provide extra protection to the child in the rearward-facing seat and is believed to be hazardous, especially for those rearward-facing seats mounted in close proximity to the dashboard.

II. METHODS

Fourty two frontal impact sled tests were performed in complete vehicle environment. The vehicle chosen was a modern passenger car, representative of a Volvo car introduced from model year 2007 and later. This front passenger airbag design is representative of modern front passenger airbags, common on the market for approximately the last decade. The airbag is top-mounted, with a size of approximately 120 litres. The deployment pattern is shown in Fig. 1, and features positioning characteristics with little or no vertical movement relative to the occupant.

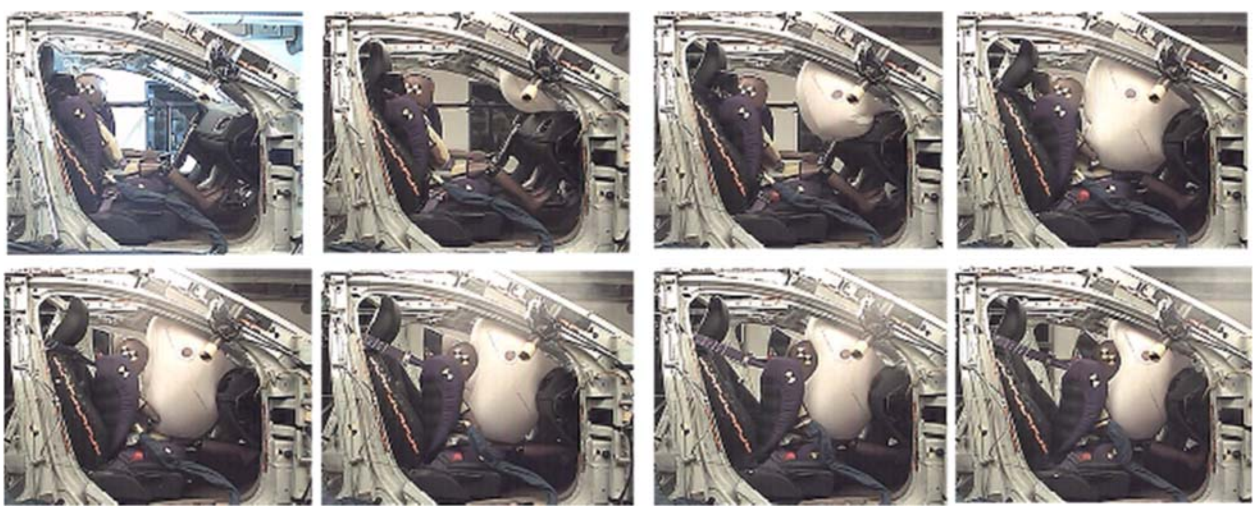

Fig. 1. Airbag deployment characteristics, from top left to bottom right.

The sled test rig comprises a complete interior of the car (Fig. 2), containing instrument panel, seat, passenger airbag, headliner, A-pillar and seatbelts. The instrument panel, passenger airbag (when activated) and seatbelts were changed after each test. Mechanical seats were used to minimise technical complexity, furthermore the seats height-adjusters, longitudinal adjustment and recliner were welded and reinforced to allow the same seat to be used in several tests.

In total, 19 different situations were evaluated, as summarised in Table I. Each situation was repeated with and without airbag activation.

TABLE I
TEST SITUATIONS INCLUDED IN THIS STUDY; EACH SITUATION WAS TESTED WITH AND WITHOUT AIRBAG ACTIVATION

Situation	**Crash pulse**	**Child dummy** (AB off/on)	**Child restraint**	**Seat position** (longitudinal+ height)	**Sitting posture /misuse**
1	A	Q3/Q3	booster seat	front + mid	upright
2	A	Q3/Q3	booster seat	mid + mid	upright
3	C	Q3/Q3	booster seat	mid + mid	upright
4	A	Q3/Q3	booster seat	rear + low	upright
5	A	Q6/Q6	booster seat	front + mid	upright
6	A	Q6/Q6	booster seat	mid + mid	upright
7	C	Q6/Q6	booster seat	mid + mid	upright
8	A	Q6/Q6	booster cushion	mid + mid	upright
9	B	HIII6y/Q6	booster cushion	mid + mid	upright
10	A	Q6/Q6	booster seat	rear + low	upright
11	B	Q6/Q6	booster seat	front + mid	forward leaning
12	B	Q6/Q6	booster seat	mid + mid	forward leaning
13	A	Q6/Q6	booster seat	mid + mid	forward leaning
14	A	HIII6y/Q6	booster seat	front + mid	belt behind back
15	A	HIII6y/Q6	booster seat	mid + mid	belt under arm
16	A	HIII6y/Q6	booster seat	mid + mid	belt behind back
17	B	HIII6y/Q6	booster seat	mid + mid	belt behind back
18	A	Q10/Q10	none	mid + mid	upright
19	A	Q10/Q10	booster cushion	mid + mid	upright

Three different crash pulses, as shown in Fig. 3, were used. They represent a selection of frontal crashes of varied overlap, impact speed and counterpart stiffness. Crash pulse A was used for most situations tested. It was selected to represent a worst-case scenario, maximising interaction between the airbag and the forward-facing child dummy. Some situations were also run with crash pulses B and C as a complement. Pulse B is different with respect to acceleration vs time characteristics, while C represents a less severe crash pulse.

Fig. 2. Sled test set-up.

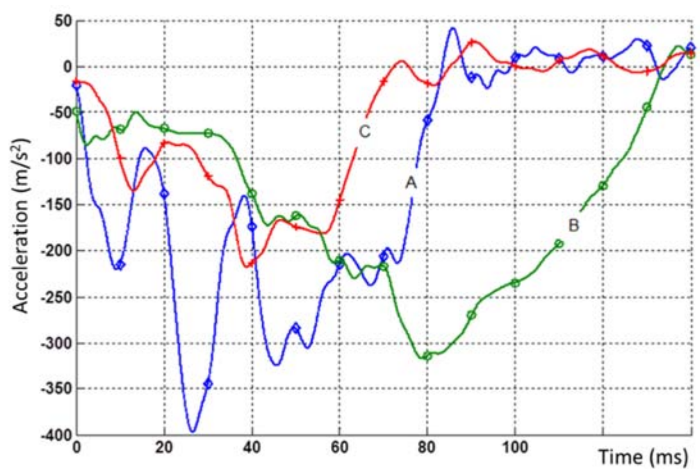

Fig. 3. The crash pulses used: blue = A; green = B; red = C.

Three different crash test dummy sizes were used: 3YO, 6YO and 10YO. In all tests, except some misuse/severe cases without airbag, the Q-series crash test dummies were used. In the misuse cases, the HIII 6YO dummy (HIII6y) was used, to avoid risking damage to the single available Q6 dummy. Seatbelts, including retractor pretensioner and two-stage adaptive load limiters (4 kN / 2 kN) were used in every test. The seatbelt setting and airbag activation were according to standard triggering principles for the vehicle concerned and the crash pulse applied. Two different child restraints were tested: a booster cushion and a booster seat. The booster seat was a Volvo-branded booster seat, similar to the Britax Kid Plus. The booster cushion was the same type of seat, but with backrest removed. The 10YO crash test dummy was also tested restrained with seatbelt only. Three different seat positions were included in the test series, with the following combinations: longitudinal/height adjustments; mid/mid; full forward/mid; full rearward/low. Two different sitting postures were tested: upright, according to standard crash test position; and a forward leaning posture. The forward leaning posture simulated a potential pre-braking before the crash. The child dummy was leaned forward 200 mm to simulate the most forward position of a child after an emergency braking of approximately 1 g [7]. The forward leaning posture was achieved by flexing the torso forward, without moving the pelvis, until 200 mm displacement of the head (centre of gravity) was reached. In addition, two typical seatbelt misuse cases were tested: shoulder-belt positioned under the arm and behind the back, respectively.

For each test situation, the dummy kinematics and responses were compared with and without the airbag activation. Some of the situations were chosen as they are frequently occurring situations, hence proving information on the potential benefit of the airbag in such scenarios. Other situations, such as the misuse and/or forward leaning posture, were chosen to evaluate the potential harm of the airbag in such a situation.

Important aspects of kinematics evaluation include dummy airbag interaction, and whether the dummy is interacting with the "moving surface" of the deploying airbag. The dummy responses for the different main body regions were compared between the tests with and without airbag activation. Published preliminary Injury Assessment Reference Values (IARV) for the Q-dummies were used to normalise the responses, enabling comparison of potential tolerance limits as well [8-10]. The IARV used in this study are shown in Table II.

For the situations where the HIII dummy was used (mainly in tests with seatbelt misuse and no airbag), detailed comparison of dummy responses was not carried out because of the mismatch in dummy models used. Instead, the dummy responses from the Q6 dummy tests were reviewed and comparison to the HIII 6YO tests was mainly via kinematics evaluation.

TABLE II

INJURY ASSESSMENT REFERENCE VALUES USED IN THIS STUDY.

	Injury Criteria	**Q3**	**Q6**	**Q10**
Head	HIC15	800 [1]	800 [1]	800 [1]
	Head resultant acceleration 3 ms (Hr)	80 g [1]	80 g [1]	80 g [1]
Neck	Neck tension (Fz+)	1.55 kN [2]	2.1 kN [2]	2.59 kN [3]
	Neck flexion (My+)	79 Nm [2]	118 Nm [2]	157 Nm [3]
Chest	Chest deflection (Cd)	36 mm[2]	33 mm [2]	56 mm [2]
	Chest acceleration 3 ms, (Cr)	55 g [1]	55 g [1]	55 g [1]

Note: [1] [8], [2] [9], [3] [10].

III. RESULTS

To different extents, all 19 situations tested demonstrated relative positive effect for activated front passenger airbag as compared to no airbag. Improved head/neck kinematics, more margin of contact to hard surfaces, along with better control of hands/arms are among the benefits of the airbag, thus providing added or comparable protection to the restrained forward-facing child. In the misuse situations (seatbelt under arm and seatbelt behind the back), it was clearly more robust using the front passenger airbag to help protect the forward-facing child. A summary of the maximum values for the injury criteria studied is presented in Table I in Appendix.

Child occupant size and seating position

Figure 4 shows the kinematics of the Q3, Q6 and Q10 in mid-mid seat position, in crash pulse A (situations 2, 6, 19). The Q3 and Q6 are using booster seat, and the Q10 is using a booster cushion. Figure 5(a)–(c) shows the normalised dummy responses for the same tests.

Fig. 4. Situations 2, 6 and 19, comparing the dummy sizes (Q3, Q6, Q10) in mid-mid seat position. *Top row:* tests without airbag; *bottom row*: with airbags. First airbag contact (*left in each pair*), and max. excursion (*right in each pair*).

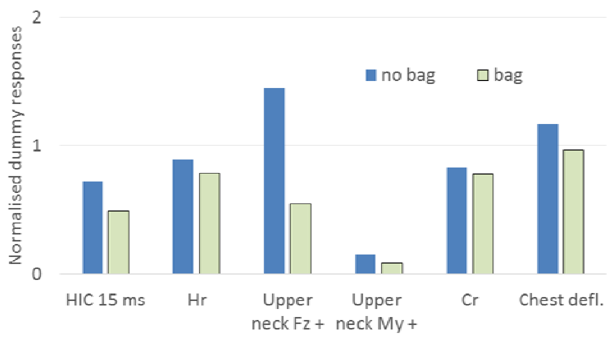

Fig. 5(a). Normalised dummy responses, situation 2. Q3 dummy in mid-mid seat position, pulse A.

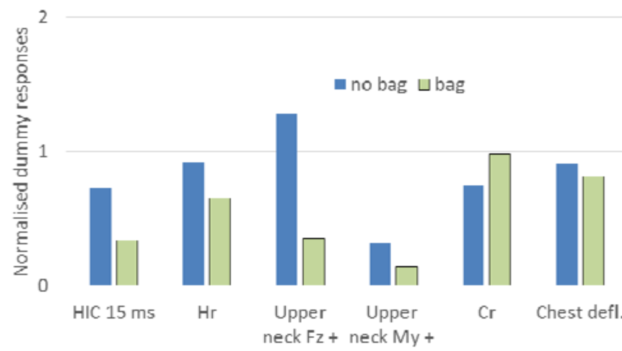

Fig. 5(b). Normalised dummy responses, situation 6. Q6 dummy in mid-mid seat position, pulse A.

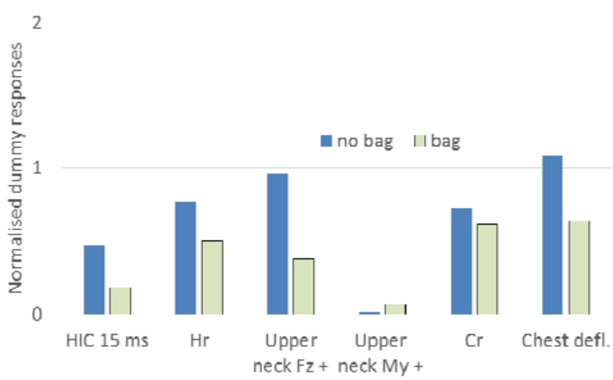

Fig. 5(c). Normalised dummy responses, situation 19. Q10 dummy in mid-mid seat position, pulse A.

Irrespective of child dummy size, the airbag is well deployed at time of head contact (Fig. 4). Thereafter, the airbag is shown to provide a good support to the head and neck, as shown by the relatively lower head and neck responses for all the three child dummy sizes (Fig. 5(a)–(c)).

Providing information on influence of seat position, Q6 in mid-mid position (situation 6, Figs 4 and 5(b)) is compared to the Q6 in forward-mid seat position (situation 5, Figs 6(a) and 7(a)) and rearward-low seat position (situation 10, Figs 6(b) and 7(b)). In the three pairs of tests, the Q6 is using a booster seat and is being exposed to crash pulse A.

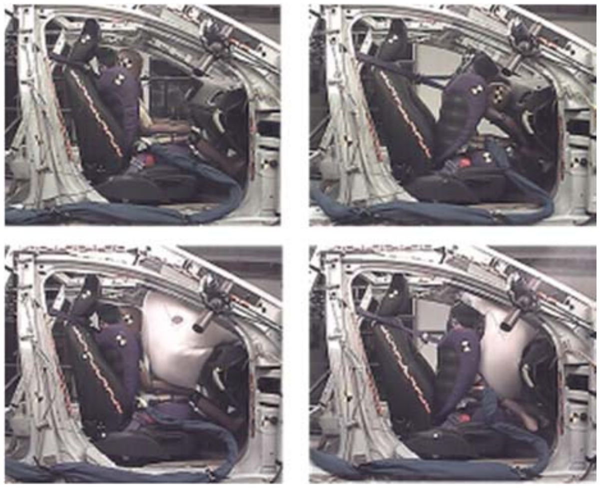

Fig. 6(a). Situation 5, Q6 in forward-mid position; *top row:* tests without airbag; *bottom row*: with airbag. First airbag contact (*left*), max. excursion (*right*).

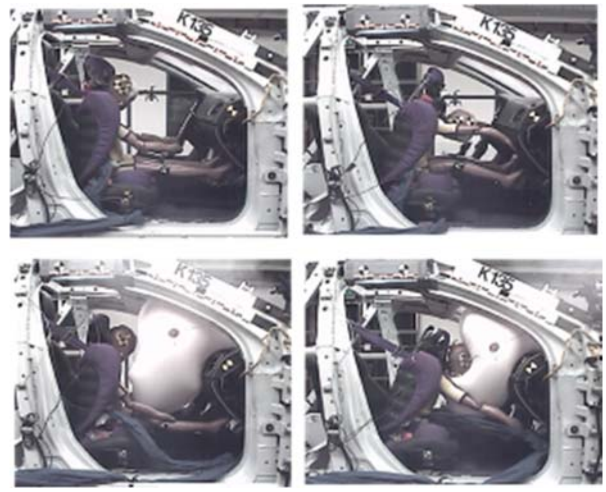

Fig. 6(b). Situation 10, Q6 in rearward-low position; *top row*: tests without airbag; *bottom row*: with airbag. First airbag contact (*left*), max. excursion (*right*).

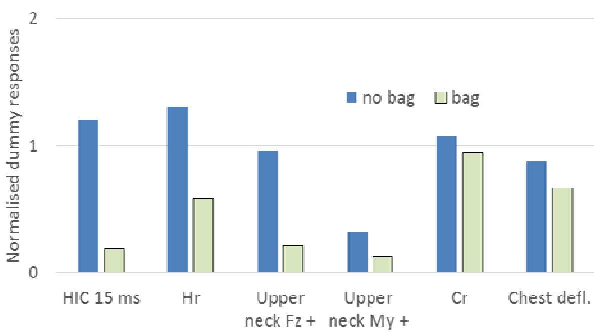

Fig. 7(a). Normalised dummy responses, situation 5; Q6 in front-mid seat position, pulse A.

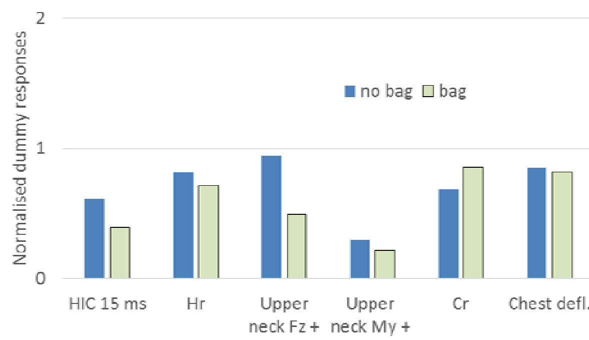

Fig. 7(b). Normalised dummy responses, situation 10; Q6 in rear-low seat position, pulse A.

The relative positive trend of airbag use is seen irrespective of seat position for the Q6. In particular, the head and neck responses are relatively lower in the tests with airbag as compared to the tests without airbag activation. The influence of the airbag was relatively more pronounced in the more forward seat adjustment positions. Test situation 5 is simulating a 6YO in a booster seat, with the front passenger seat in the most forward and upward position. Although probably not the most common seating position, the results indicate that the airbag likely will add protection in this situation. As can be seen in Fig. 6(a), the Q6 sustains a head impact into the dashboard, resulting in high head accelerations, which are significantly reduced in the test with airbag activation (Fig. 7(a)).

Child restraints

Most of the tests were run with a booster seat. For comparison, tests with booster cushion were run for Q6 in mid-mid seat position in crash pulse A. Comparing the kinematics and dummy responses for the Q6 on booster cushion (situation 8, Figs 8 and 9) with the same set-up but with a booster seat (situation 6, Figs 4 and 5(b)), the same trends can be seen with respect to airbag versus no airbag. The relative positive effect of airbag is most pronounced for the situation with booster seat. This is mostly related to the relatively higher head and neck responses for the booster-seated child, likely due to differences in initial sitting posture and position. The Q6 on booster cushion (situation 8, Fig. 9) is rather similar in its responses to the tests with Q6 in booster seat seated in most rearward seat position (situation 10, Fig. 7(b)). This makes sense since a child in a booster seat will be positioned further forward, as compared to on a booster cushion, due to the backrest of the booster.

In addition, tests were run without child restraint for the Q10 dummy in mid-mid position (situation 18). The influence of the airbag follows the same trend as seen for the Q10 using booster cushion (situation 19), (Table I in Appendix). Especially for the neck loads, a relative difference is seen, with the airbag helping to reduce the values below the IARV.

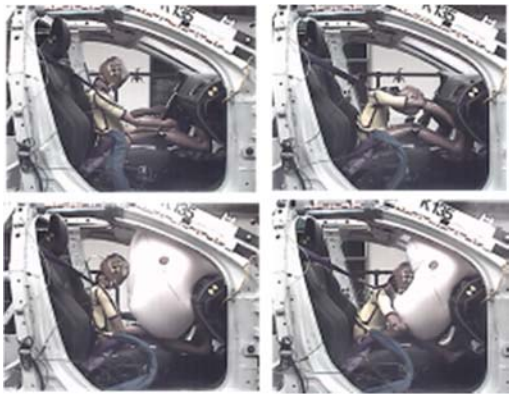

Fig. 8. Situation 8, Q6 on booster cushion, mid-mid seat position; *top row*: tests without airbag; *bottom row*: with airbag. First airbag contact (*left*), max. excursion (*right*).

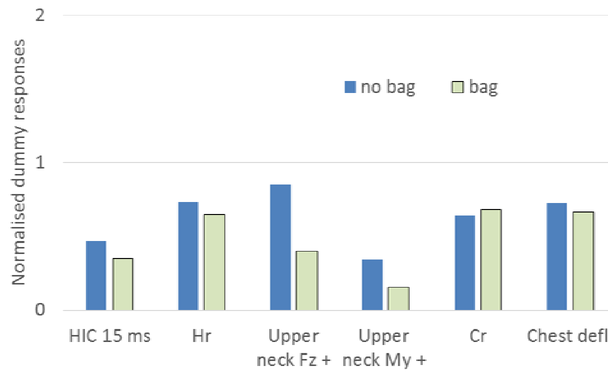

Fig. 9. Normalised dummy responses situation 8; mid-mid seat position, Q6 dummy on booster cushion, pulse A.

Crash pulse influence

To evaluate the influence of crash pulse, some tests were run in comparable set-up, only changing the pulse. The Q3 (situation 3) and Q6 (situation 7) in mid-mid seat position, exposed to crash pulse C, is compared to similar test set-up exposed to crash pulse A (situations 2 and 6, respectively). Crash pulse C is a relatively low severity pulse. As can be seen in Fig. 10(a) and (b), the dummy kinematics is influenced by the crash pulse, with a less forward excursion in pulse C, as compared to comparable test in pulse A; situations 2 and 6 (Fig. 4). When comparing pairwise with respect to airbag influence, the same trend is seen, irrespective of pulse. The dummy responses for the Q3 are shown in Fig. 5(a) and Fig. 11(a), while the Q6 responses are shown in Fig. 5(b) and 11(b). The pairwise comparison of dummy readings for crash pulse C follows the trend as for crash pulse A, although with lower overall values due to lower severity crash pulse.

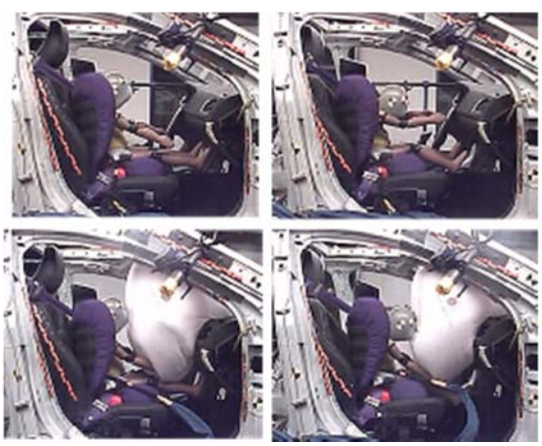

Fig. 10(a). Situation 3, Q3, mid-mid seat position, crash pulse C; *top row*: tests without airbag; *bottom row*: with airbag. First airbag contact (*left*), max. excursion (*right*).

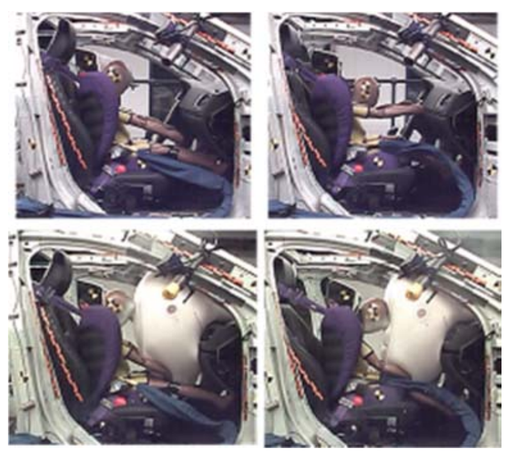

Fig. 10(b). Situation 7, Q6, mid-mid seat position, crash pulse C; *top row*: tests without airbag; *bottom row*: with airbag. First airbag contact (*left*), max. excursion (*right*).

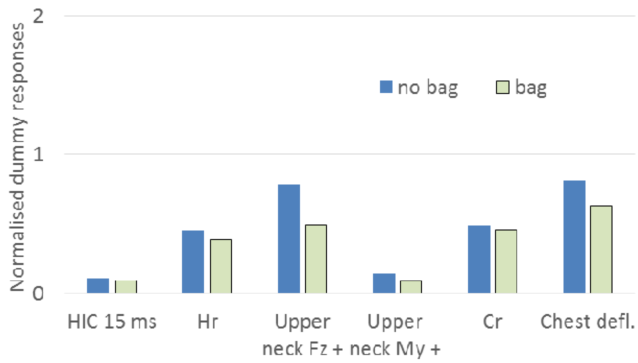

Fig. 11(a). Normalised dummy responses situation 3; Q3 on booster seat, mid-mid seat position, crash pulse C.

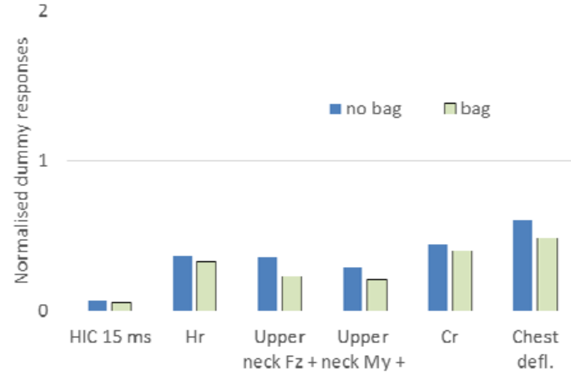

Fig. 11(b). Normalised dummy responses situation 7; Q6 on booster seat, mid-mid seat position, crash pulse C.

In addition, tests were run with the pulse B (situation 9) and Q6 using booster cushion, in mid-mid seat position. When compared to test situation 8 (Figs 8 and 9), the same trend for airbag versus no airbag is seen. Since one of the tests in situation 9 was run with the HIII 6YO dummy, no exact comparisons can be made in dummy responses.

Forward leaning / pre-brake situation

Three test situations were run with a Q6 in a forward leaning mode to simulate a pre-brake situation. Situations 12 and 13 are in mid-mid seat position. Two different pulses were used (B and A, respectively) to check the influence of the pulse shape with respect to timing and airbag interaction. The kinematics for these tests are shown in Fig. 12 and the dummy responses are shown in Fig. 13.

Fig. 12(a). Situation 12, Q6 forward leaning, mid-mid seat position, pulse B; *top row*: tests without airbag; *bottom row*: with airbag. First airbag contact (*left*), max. forward position (*right*).

Fig. 12(b). Situation 13, Q6 forward leaning, mid-mid seat position, pulse A; *top row*: tests without airbag; *bottom row*: with airbag. First airbag contact (*left*), max. forward position (*right*).

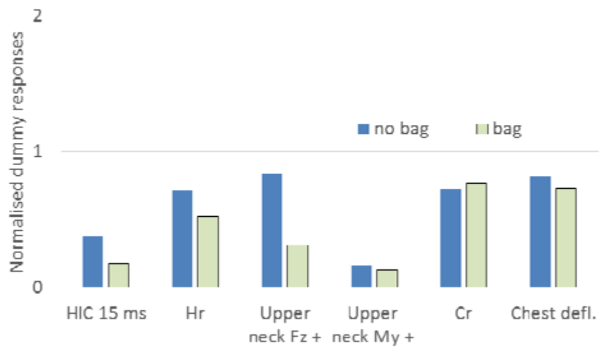

Fig. 13(a). Normalised dummy responses situation 12; Q6 on booster seat forward leaning, mid-mid seat position, pulse B.

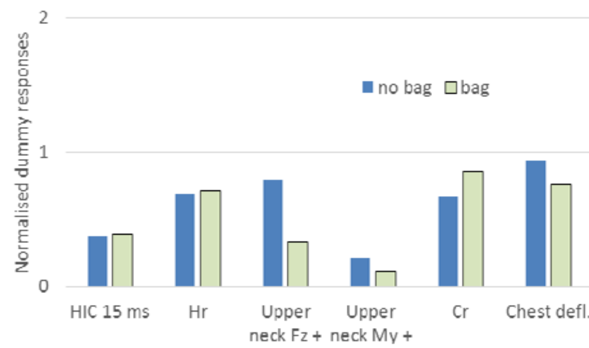

Fig. 13(b). Normalised dummy responses situation 13; Q6 on booster seat forward leaning, mid-mid seat position, pulse A.

To evaluate if a more forward initial seat position would differ from a mid-mid seat position, a test was run with a forward leaned Q6 on booster seat in the most forward seat position (situation 11). Crash pulse B was selected for this test. The kinematics for these tests are shown in Fig. 14 and the dummy responses are shown in Fig. 15. The occupant responses are well below the limit of IARV, and the airbag adds protection to the neck as well as to the chest. Although being an unlikely seating position, this was run to ensure a good airbag positioning, which was confirmed (see Fig. 14).

Fig. 14. Situation 11, Q6 forward leaning, forward seat position, pulse B; *top row*: tests without airbag; *bottom row*: with airbag. First airbag contact (*left*), max. forward position (*right*).

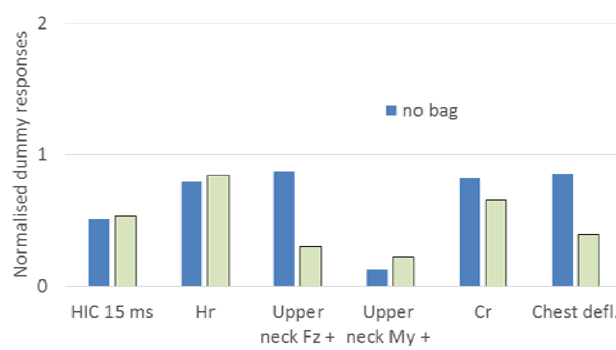

Fig. 15. Normalised dummy responses situation 11; Q6 on booster seat forward leaning, forward-mid seat position, pulse B.

Seatbelt misuse

Two different situations of seatbelt misuse were tested to evaluate the effect of an airbag interaction with a child that was not restrained appropriately. In situation 15 (Q6, mid-mid, seat position, pulse A), the belt was placed under the arm. Two tests were performed in mid-mid position using the Q6 with the seatbelt placed behind the back, pulse A (situation 16) and pulse B (situation 17), respectively. In addition, the Q6 dummy with the seatbelt placed behind the back (pulse A, test situation 14) was tested in the front-mid position as well. Dummy kinematics for all tests are shown in Fig. 16(a)–(d).

In all cases of airbag activation, the responses were well below the IARV values. For the non-airbag cases, the responses were multiple times higher, especially for the head, due to severe head impact into the dashboard. As the HIII 6YO was used in the non-airbag tests, no detailed dummy response comparisons are made (values are presented in Appendix, Table I).

Fig. 16(a). Situation 15, HIII6y /Q6, belt placed <u>under the arm</u> mid-mid, seat position, pulse A; *top row*: tests without airbag; *bottom row*: with airbag. First airbag contact (*left*), max. forward position (*right*).

Fig. 16(b). Situations 16, HIII6y/Q6, belt placed <u>behind the back</u> mid-mid seat position, pulse A; *top row*: tests without airbag; *bottom row*: with airbag. First airbag contact (*left*), max. forward position (*right*).

Fig. 16(c). Situation 14, HIII6y/Q6, belt placed <u>behind the back</u>, front-mid seat position, pulse A; *top row*: tests without airbag; *bottom row*: with airbag. First airbag contact (*left*), max. forward position (*right*).

Fig. 16(d). Situation 17, HIII6y/Q6, belt placed <u>behind the back</u> mid-mid seat position, pulse B; *top row*: tests without airbag; *bottom row*: with airbag. First airbag contact (*left*), max. forward position (*right*).

IV. DISCUSSION

The situations in the test series were chosen to provide information facilitating a comparison on whether a restrained forward-facing child occupant sitting in the front passenger seat would benefit from an activated airbag in a frontal impact. The airbag improvements (especially with respect to inflator and folding techniques), and due to the fact that the seatbelt developments are driven together with airbags (whereby no stand-alone seatbelt evaluation is forced to be made) motivate this study. The results are primarily targeting countries in which the front seat may be used by child passengers and where it is required to actively switch on/off the front passenger airbag depending on who is occupying the seat. In the test series, the seat positions and child occupant sizes were combined to cover the most common positions, as well as including some extreme positions. Different child restraints, as well as a variety of crash pulses, were used in order to ascertain whether any major differences applied. In addition, some misuse cases were included to ensure that the child occupant injury risk would not be increased by activation of the airbag. Unrestrained was not considered, since the purpose of the study was to provide improved quality in disabling/enabling guidelines and not to evaluate the whole context of children in the front seat and interaction to airbags.

The contribution of the airbag was relatively more pronounced in the more forward seat adjustment positions, and less distinct in the more rearward seat adjustment positions. This is natural, as in the forward seat positions there is a higher likelihood of occupant interaction with the dashboard, in situations with no airbag activation. In addition, the airbag interaction is less noticeable when the seat is moved backwards. The airbag helped not only to avoid head impacts but also provided a support in controlling the kinematics of the torso and neck, as well as the hands and arms. In the misuse situations (seatbelt under the arm and seatbelt behind the back), it was clearly more robust using the front passenger airbag to help protect the forward-facing child.

IARV values based on partly preliminary references for the UN/ECE/R129 were chosen to provide a normalisation of the dummy responses. The purpose was to make the comparison easier, and should not be used to provide absolute comparison to potential injury threshold. In some tests, the test results were higher than the IARV values, mainly as a result of severe frontal impact situations (e.g. severe crash pulses, head impacts). As stated by the references [6, 7] some of the chosen IARV values were preliminary and limited in evaluation. Despite this, for the purpose of this study it served to compare the relative difference.

Four of the test situations were repeated, providing insight into test variability. Comparing these pairs of tests, it was seen that the response variability was within range of 10% for the head and neck, except for some very small values. Chest resultant acceleration could not be evaluated, due to some sensor failure, while the Cd variability in some cases was above 10%. Some of the Cd variation could be explained by the different placement of the shoulder-belt load sensor between the tests, which influenced the seatbelt pretensioning to some extent. Another test set-up variability was the placement of the arms, which varied somewhat between some of the tests. The effect of this variability on dummy responses is judged to be minor.

The kinematics and responses of a front seat occupant are influenced by the seatbelt characteristics (pre-tensioner and load limiting). The setting of the seatbelt characteristics depends on several factors, one of them being airbag activation. This means that there are some differences in seatbelt characteristics as part of the varied variables between the comparable test pairs, since the seatbelt characteristics were chosen according to the specification for the vehicle used in the test. This choice was made as it would be the true comparison with respect to airbag enable or disable setting. Some additional tests (not included in this paper) were run to check the influence of the seatbelt characteristics. The results from those tests provided evidence that the influence of this factor did not change the overall conclusions with respect to effect of airbag activation.

Booster seat was chosen for all the 3YO tested and most of the 6YO tested; while booster cushion as well as no booster was chosen for the 10YO. No major differences are seen between the different restraint types. In some countries, forward-facing child seats with internal harness are used for the youngest/smallest within the range of tests in this series. This type of seat was not included in this test series and might need further testing if judged not represented by the variation of tests (in position tests as well as misuse situations) performed in this study.

In EU countries it is regulated by law that the front passenger airbag must be disabled when a rearward-facing child occupies the front seat. Johannsen *et al*. [3] proposed that it might be feasible to design a front passenger airbag to be compatible with rearward-facing infant seats. However, the rearward-facing seats come in different sizes, including toddlers as well. These larger rearward-facing toddler seats are very different from the infant seats and are placed higher and in closer proximity to the instrument panel. They will most likely not benefit from an airbag activation, and could even be harmed by it.

Based on the results in this study, together with additional airbag deployment studies, Volvo Cars is revising its recommendations for restrained forward-facing children travelling in car models with front passenger airbag designs as tested in this study. For these specific car models it is recommended that the airbag should be Enabled for all forward-facing restrained child occupants (as for adults), while kept Disabled for all rearward-facing children. This type of airbag design (Fig. 1) is a common design in modern vehicles and it is encouraged that other car models are exerted for the same type of evaluation to establish if this will be applicable for a wider range of vehicles, in countries where children are allowed to sit in the front seat. An airbag disabling strategy that distinguishes between rearward-facing and forward-facing occupants is easier to communicate and to remember than age- or height-specific recommendations. By being more clear in its limits, such a strategy will most likely help to reduce the misuse cases and provide enhanced protection not only for the child occupants benefiting from the modern airbag design but also for adult occupants, who might otherwise have been without airbag protection.

V. CONCLUSIONS

This study shows that a modern front passenger airbag, as tested in this study, can enhance protection to restrained forward-facing children (3YO–10YO). To different extents, all 19 situations tested demonstrated relative positive (or comparable) effect for activated airbag compared to no airbag. The contribution of the airbag was relatively more pronounced in the more forward seat adjustment positions, and less distinct in the more rearward seat adjustment positions. Improved head/neck kinematics, more margin for contact with hard surfaces, along with better control of hands/arms are among the benefits of the airbag, thus providing added protection to the forward-facing child. In the misuse situations (seatbelt under arm and seatbelt behind the back), it was clearly more robust using the front passenger airbag to help protect the forward-facing child.

Based on the results of this study, Volvo Cars is revising its recommendations for restrained forward-facing children travelling in car models with front passenger airbag designs as tested in this study. For these specific car models it is recommended that the airbag should be Enabled for all forward-facing restrained child occupants (as for adults), while kept Disabled for all rearward-facing children.

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VII. Appendix

TABLE I

SUMMARY OF MAXIMUM VALUES FOR STUDIED INJURY METRICS. THE TESTS WITH GREY SHADOWS ARE WITH HIII6Y DUMMY, AND SHOULD NOT BE COMPARED WITH THE OTHER TEST RESULTS (WITH Q-DUMMIES).

Situation	Airbag	HIC 15 [ms]	Hr (3 ms) [g]	Fz+/Fz- [N]	My+/My- [Nm]	Cr (3 ms) [g]	Cd [mm]
1	Off	583	71	2630 / -7	12 / -12	N/A*	34
1	On	303	58	394 / -161	9 / -8	N/A*	31
1	Off	572	71	1990 / -11	15 / -8	44	42
1	On	273	52	492 / -208	9 / -8	49	31
2	Off	596	72	2360 / -6	13 / -10	N/A*	38
2	On	427	64	877 / -116	5 / -13	N/A*	27
2	Off	563	71	2140 / -4	12 / -9	46	37
2	On	371	62	827 / -33	9 / -12	43	35
3	Off	89	36	1220 / -7	11 / -7	27	26
3	On	73	31	761 / -9	7 / -6	25	20
4	Off	862	82	2170 / -213	10 / -11	59	31
4	On	526	72	1460 / -184	12 / -15	52	22
5	Off	968	105	2010 / -6	38 / -10	59	29
5	On	151	47	448 / -444	15 / -10	52	22
6	Off	581	74	2690 / -7	38 / -7	41	30
6	On	267	52	746 / -649	17 / -15	54	27
7	Off	53	29	740 / -6	34 / -8	24	20
7	On	45	26	488 / -38	25 / -7	22	16
8	Off	373	59	1780 / 0	40 / -7	35	24
8	On	276	52	834 / 0	18 / -18	38	22
9	Off	215	48	1580 / -58	8 / -9	37	38
9	On	305	54	795 / -33	18 / -6	41	25
10	Off	492	65	1980 / -85	35 / -11	38	28
10	On	314	57	1040 / -67	26 / -34	47	27
11	Off	412	64	1820 / -4	15 / -9	45	28
11	On	425	67	628 / -1020	26 / -13	36	13
12	Off	302	57	1760 / -4	19 / -7	40	27
12	On	140	42	657 / -161	15 / -20	42	24
13	Off	294	55	1660 / -7	24 / -8	37	31
13	On	313	57	701 / -415	13 / -12	47	25
14	Off	2952	144	6760 / -103	3 / -120	108	50
14	On	113	38	332 / -390	15 / -10	51	8
15	Off	2476	190	2640 / -1590	49 / -57	65	55
15	On	211	48	624 / -270	21 / -18	48	15
16	Off	1672	165	3220 / -94	85 / -57	70	23
16	On	299	55	411 / -239	21 / -15	51	7
17	Off	2815	152	2970 / -1760	161 / -35	61	22
17	On	392	60	335 / -154	6 / -21	51	6
18	Off	877	86	4650 / -23	21 / -21	47	24
18	On	594	77	1150 / -19	8 / -27	44	27
19	Off	374	62	2500 / -11	3 / -12	40	61
19	On	147	40	993 / -16	10 / -25	34	36

Note: *When multiple responses are available, the average values are used.*

** Not applicable due to sensor failure*