STUDY OF SECOND ROW OCCUPANT PROTECTION IN FRONTAL VEHICLE CRASHES AND POTENTIAL RESTRAINT SYSTEM COUNTERMEASURES

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ABSTRACT

Legal requirements regarding the qualification of the second seat row restraint system with anthropomorphic test devices (ATDs) currently do not exist. Consumer tests with respect to mass production rear occupant protection systems are already being planned or even executed and the results are or will be publicly available. However, there are various factors that make it difficult to apply the strategies applied for first row occupants to second row occupants. Also, there are differences regarding seat deformation and applied decelerations relative to the first row occupants. The purpose of this study is to evaluate the effectiveness of various restraint system components for second seat row occupants.

Sled tests with different occupant sizes have been conducted and analyzed in the second seat row. Based on these tests, a numerical simulation model has been built and correlated for various crash modes. Investigations were conducted that evaluate the relevant restraint parameters and their impact on the occupant protection performance for second seat row occupants. Restraint components have been modified in order to determine their potential to enable a premium rating under the current consumer test protocols for second row occupants.

A reduction of the external loads applied to the ATD due to the use of pyrotechnic seat belt pretensioners and seat belt load limiters has been shown. Low force levels result in increased displacement of the occupant's head and thorax and therefore increases the risk of occupant contact to the vehicle interior components. The potential of controlling the head kinematics with the seat belt alone without the addition of other restraint components is limited. A conventional 3-point seat belt seems to be insufficient to secure premium ratings for future consumer test programs. Additional inflatable devices like an airbelt allow a further reduction of the occupant loads with comparable or even reduced occupant displacement. Adaptive seat belt components with selectable force levels are recommended since this technology allows a reasonable trade-off between reduced occupant loads and controlled occupant displacement for various occupant sizes. Additional influencing factors for the occupant loads have been identified, including: the mechanical and geometrical properties of the seat ramp, and the timing and intensity of the vehicle pitch.

INTRODUCTION

Accident statistics over the last decades have shown a continuous reduction of killed and severely injured passengers [1]. This development was driven forward by new legislative requirements and the introduction and continuous progress on worldwide consumer test programs like the Euro-NCAP. The user's consciousness on safety is continually increasing due to publications and public discussion of road safety issues. Car manufacturers, in cooperation with suppliers, have taken massive action in order to achieve a top rating in consumer tests. The equipment rate of active and passive elements is steadily increasing and allows predicting further positive effect on road safety for the future.

Several recent publications discuss the passenger safety of the second row. Kuppa et al. [2] indicate higher mechanical loads on back seat passengers during a crash and deduce a higher injury risk compared to drivers and passengers in the first row. Restraint components like inflatable cushions (airbags) in order to protect the head and thorax or the lower extremities as well as pyrotechnical pretensioners partly with multi-stage load limiters for belt retractors are standard equipment in the front seat row.

The next generation is already under development. Individualized restraint systems, like those providing adaptive pressure control of the airbag pressure and multi-stage belt force limitation concepts, are pending market introduction. These systems enable tailored restraint performance depending on crash severity and occupant size. In contrast to this, a 3-point belt retractor without pretension and force limitation is still the standard for the back seat passengers.

These recent studies confirmed the effectiveness and the benefit of using a pyrotechnical pretensioner and belt force limiter for back seat passengers in order to reduce the occupant loads in frontal crashes. Forman et al. [3] highlighted significantly decreased chest loads in tests with ATDs if a pyrotechnical pretensioner and an adapted belt force limitation is applied for rear seated occupants. Stegmeier et al. [4] stated belt pretensioner and belt force limiter are recommended all times. However, full adaptive load limiters are required to cover all dummy sizes. Each configuration requires an adjusted load level in order to reduce the injury risk to a minimum.

Consumer protection organizations incorporated adult passengers on the back seat in their frontal test programs. The Hybrid III ATD with the 5th percentile is already an element of a test configuration for China-NCAP [5] and Japan-NCAP [6]. Euro-NCAP [7] announced a follow up in 2015. Figure 1 gives an overview of recent and future crash test configurations for worldwide consumer tests focused on back seat passengers:

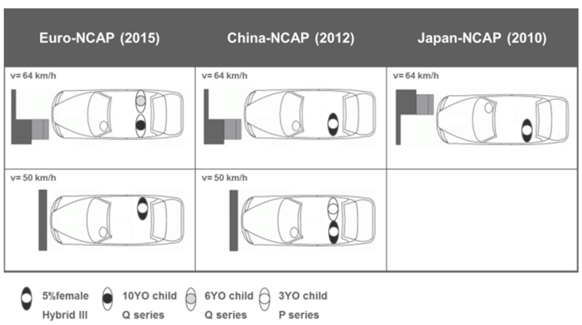

Figure1. Recent and future rear seat consumer test configurations.

The challenging requirements by NCAP programs and their continuous amendment feed the prediction that standard measures like pyrotechnical pretensioners and belt force limitation are not sufficient to achieve a top rating for the second row in the long- term.

ACCIDENT STATISTICS

An evaluation of the GIDAS database effective January 2011 exposed a lower occupation rate of the back seats compared to the driver seat and passenger seat in Germany. Single collisions with frontal impact direction and belted passengers have been considered for the next steps only. Figure 2 shows the distribution of the seat occupation of all passengers involved in those accidents.

The occupation rate for all back seats is close to 10 percent. Compared to the first row passengers, driver and front passenger, this percentage appears low.

Figure 3 highlights the gender specific distribution of back seat passengers. A similar ratio to the German population can be observed if all injured and not injured passengers are considered. With increasing injury severity a trend is observable. The percentage of female passengers is increasing.

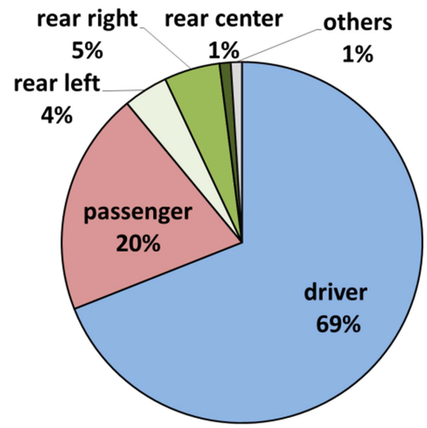

Figure2. Distribution on seating position, N=10.551 (source: GIDAS).

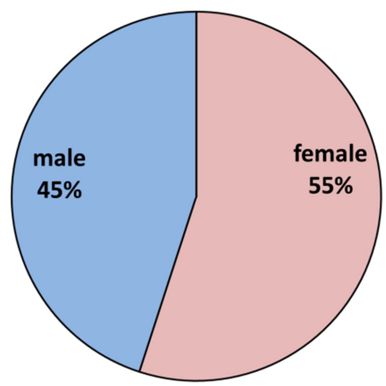

Figure3. All MAIS – gender distribution, N=806 (source: GIDAS).

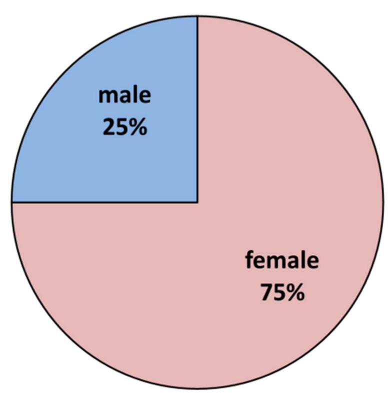

Figure4. MAIS 2+ - gender distribution, N=44 (source: GIDAS).

Figure 4 shows the gender distribution of back seat passengers which are subjected to an injury severity level of MAIS 2+. At this severity the portion of female passengers is close to 75 percent.

More than 50 percent of MAIS 2+ injured back seat passengers in the documented cases are between 150 cm and 170 cm tall. Figure 5 displays the distribution of the occupant height clustered in 3 groups.

Most frequently injured body regions are with 80 percent head and chest and upper extremities on rear occupants with a total injury severity level of MAIS 2+. AIS 2+ Neck injuries are rather rarely observed. The injury-causing component has been identified according to the database. Injuries of the head region are mainly caused by the contact with first row's seat back and the contact with the own extremities. Chest injuries are induced by the interaction with the seat belt webbing. The distribution of injury-causing components appears similar between female back seat passengers and male back seat passengers.

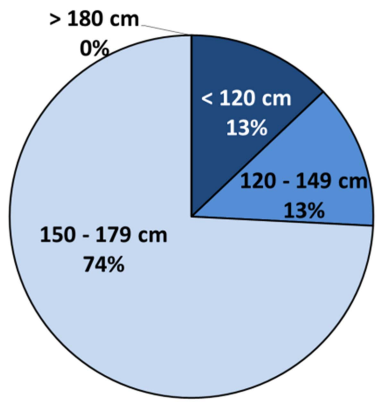

Figure5. Height distribution MAIS 2+ passengers, N=31 (source: GIDAS)

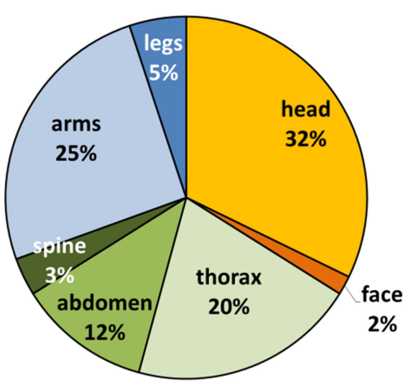

Figure6. AIS 2+ injuries by body region, N=59 (source: GIDAS)

The evaluation of the accident data indicates that small and medium female back seat passengers are one focal group in order to improve the passenger safety for rear seats.

RESULTS AND INTERPRETATION

Method

The experimental testing was done by sled tests. A body in white of an executive compact vehicle has been reinforced and adapted to the sled test facility. An extensive test matrix has been conducted with several frontal impact types equipped with adult and child dummies.

Primary test configuration has been a frontal crash with a crash pulse of 50 km/h against a flat full width barrier. Tests with Hybrid III ATDs with 5th and 50th percentile have been conducted. All passengers were protected by at least a 3 point seat belt. The first row seat was adjusted to a middle position. Test results in this configuration are shown in the following sections.

A market study confirmed a back seat passenger in mass production vehicles is protected by fewer safety components than occupants in the first seat row. Frontal airbags are not a standard yet. The recorded femur forces in this test configuration were low. In almost every test the femur compression did not exceed a level of 0.4 kN.

Seat structure

Most influencing components on the injury level of a rear seated occupant in a standard safety setup are the seat structure and the seat belt unit. The seat ramp is structure-integrated in most passenger cars. An easy replacement of the seat ramp or the seat unit after a test similar to the first seat row is not feasible. The deformation of the seat structure is dependent on crash pulse severity and occupant mass. It has been observed that components like the fuel tank and fuel pumps installed below the seat ramp might impact the occupant loads since they come in contact with the seat ramp after a certain deformation. If a seat ramp deformation is intended in the development methodology, multiple use of a car body is therefore limited. Reinforcements of the seat ramp in order to keep the seat ramp's geometry have a considerable impact on the dummy loads.

Figure 7 displays the impact on the dummy loads depending on the seat ramp stiffness. Exemplary tests with a stiff seat ramp (reinforced, no deformation) and a production seat ramp without any tank support have been compared. The injury values with a reinforced seat ramp decreased. Moreover, the seat structure is an important restraint factor since the deformation behavior influences the interaction between dummy and lap belt portion (sub-marining tendency) with possible abdominal injuries.

The dummy loads are normalized with selected Euro-NCAP's lower performance reference values (5th percentile female: discussed reference values; table 1, appendix). In particular, the head and neck injury values dropped with the use of the reinforced seat ramp. The measured forward excursion of the dummy's chest was slightly lower. Even though no head contact has been observed, the HIC value was considered for the assessment.
The results confirm that it is essential to recreate the real seat structure stiffness in order to produce correlating sled test results for a prediction of a full scale crash.

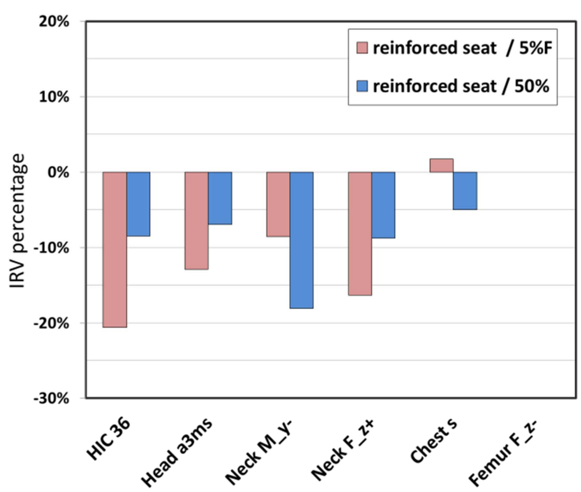

Figure7. Change in injuries level with reinforced seat structure.

Vehicle pitch

The vehicle kinematics is very complex in certain full scale crash configurations. As observed in tests with offset deformable barrier (ODB), several vehicles tend to have clearly visible rotational motion around the Y and Z axes (pitching and yawing). This motion is well visible in the test movies. The pitching behavior can be detected in full width barrier tests too. However, the motion is less noticeable in the crash movie. The measured acceleration occurs with shorter duration and at a different starting point compared to ODB tests. An evaluation of a wide range of crash pulses highlighted a widespread variety of different pitching pulses. A standard pitching crash pulse has not been identified yet.
A CAE model based on an executive compact vehicle has been validated in order to identify the impact from pitching on the occupant kinematics as well as on the injury values. The most important factors of the complex pitching movement should be identified. Several factors listed below have been considered:

- Z acceleration level, Z acceleration duration, starting point of Z acceleration
- Dependence on the X pulse characteristics
- Center of rotation

Based on the CAE results the most influencing factor is the character of the Z pulse applied to the structure of the back seat. An impact on the occupant kinematics and forward excursion was detected. Furthermore, the characteristics of the belt forces and the seat ramp contact are influenced that ultimately led to changed dummy loads.
A pitching pulse was chosen that correlates to real crash data and a sled test matrix have been conducted. Figure 8 shows the deviation of pitching sled tests with reinforced and deformable seat ramp compared to non-pitching tests. Both configurations show the same trend.
The sled tests confirmed the previous CAE study. The peak loads as well as the load curve time history change depending on the shape, the height and the duration of the pitching acceleration.

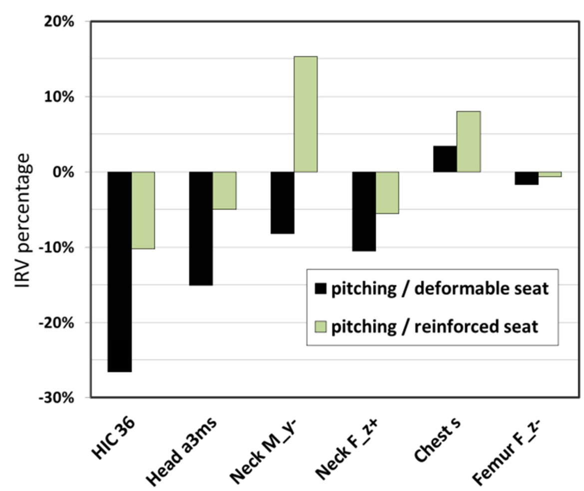

Figure8. Change in injuries level with vehicle pitch (5%ile female).

Restraint components

As a result of the developments in the NCAP programs, some rear safety layouts might be adjusted in order to keep a top level rating. The configuration with the 5th percentile ATD is a central load case. Internal investigations proved that the new NCAP requirements are challenging for chest deflection and neck loads. In particular, pyrotechnical pretensioners and belt force limiters allow addressing the chest deflection while a certain level of the head's forward excursion is not exceeded.

A reduction of the belt force level is possible to a certain extent only. Component requirements like the ECE R16 must be met and a head contact to the front seat or the own extremities should be avoided. Figure 9 shows the comparison of sled tests with different belt layouts. The images display the maximum forward excursion shortly after t= 100 ms.

Figure9. Forward excursion with different safety belt layouts (5%female).

The motion analysis also confirmed that a belt-only restraint is not capable of controlling the head and neck kinematics as done by the airbag in the first seat row. With a low belt force, which appears to be very beneficial for the chest deflection the head comes very close to the knees.

Figure 10 shows the benefit for a small female dummy compared to the standard 3 point seat belt restraint without pretension and without force limitation. Most of the dummy loads in the baseline test clearly exceeded Euro-NCAP’s lower performance level. Even though the integration of a pretensioner and a force limiter provide a substantial benefit, a clear margin remains before dropping the injury values below the higher performance level.

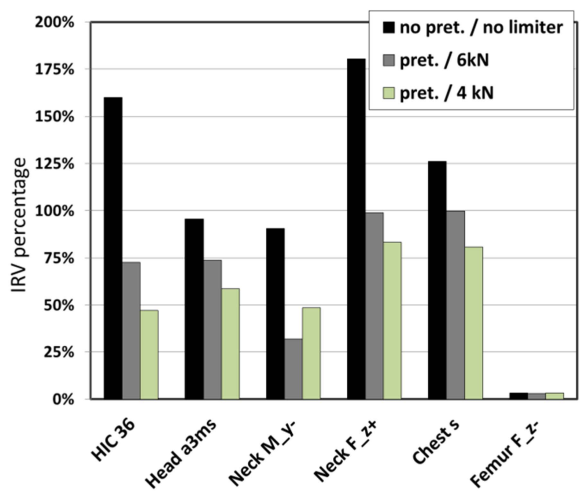

Figure10. Dummy load reduction with retractor pretension and belt force limitation

Figure11. Advanced restraint components in operation / airbelt (5%female)

Advanced components are capable of achieving a further load reduction. Additional sled tests have been conducted. An airbelt was integrated into the sled buck and the retractor force level has been adapted. This setup generates a similar head contact risk compared to the baseline test with belt force limitation and pretension. The airbelt is characterized by an inflatable portion integrated in the chest belt segment. This component is designed to distribute the restraint forces applied to the chest portion. The operation in a test is shown in figure 11.

The test results are shown in figure 12. The results are displayed in comparison to an already optimized rear safety setup with retractor pretension and a linear force limitation of 6 kN. The occupant loads have been reduced further. In particular, chest deflection and the neck tension forces have been lowered up to 40%.

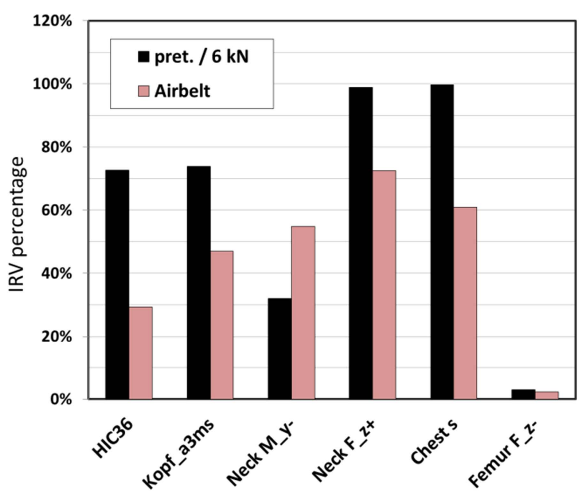

Figure12. Comparison of occupant loads (3 point belt vs. airbelt)

In further tests an inflatable head restraint has been added and optimized. The inflatable head restraint is designed to control the head and neck kinematics. The intention is to couple the head mass with the airbag which generates positive effects for the chest region too. The concept of the head airbag is shown in figure 13.

In order to mitigate chest injuries low, belt forces are required for the cases with small occupants like children and small female adult passengers. As shown before, taller adult passengers in combination with a severe crash pulse, are subjected to a certain risk of head contact with the front seat and with other interior parts or with the own extremities if the force level of a belt-only restraint is adjusted to address the rear seat NCAP configuration only. The inflatable head restraint enables controlling the upper torso motion and the head contact risk respectively while keeping the beneficial belt force level for the chest deflection. The results with head airbag compared to a standard 3 point belt restraint system with pretension and force limitation of about 6 kN are shown in figure 14. The combination of an adjusted belt force limitation in combination with the head airbag provides a balanced load distribution.

Figure13. Advanced restraint components in operation / head airbag (5%female)

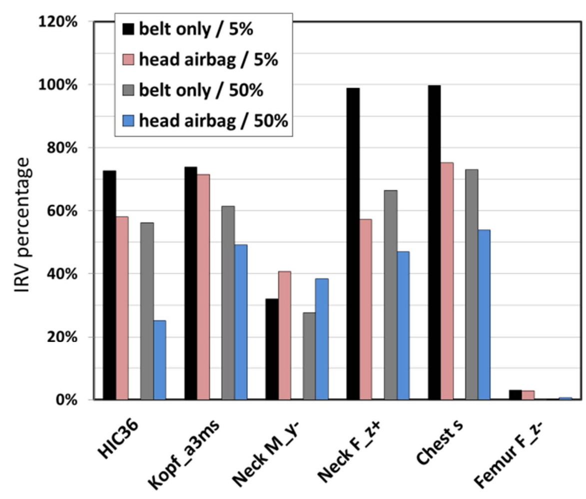

Figure14. Comparison of occupant loads (3 point belt vs. head airbag)

SUMMARY

Recently published investigations on countermeasures for reducing loads on back seat passengers have been confirmed. Pyrotechnical belt pretension and belt force limitation appear very beneficial. These measures are necessary at least for achieving a top rating in NCAP tests. However, seat belt restraints alone are not capable for controlling the head and neck kinematics. Advanced components offer an additional benefit with a further reduction of the dummy loads. In comparison to the first seat row an integration is recommended in order to establish a similar level of restraint system performance for rear seat passengers.

The methodology for setting up rear seat restraint systems needs to be adapted. Vehicle pitch and the seat ramp behavior are essential factors for some vehicles. Those factors need to be considered since they can clearly affect the overall level of the dummy loads respective to the NCAP rating.

OUTLOOK

Human body model

An Investigation with a human body model has been initiated as a part of this project. The existing rear seat CAE model has been modified. A human body model based on the 50th percentile male has been added. This previously validated Takata in-house full human body model was further developed. The upgraded model (named as TKHM v4.0) was integrated with latest developed refined body region models of the thorax, the shoulder and upper extremities, the abdomen, and the pelvis. These body region models were constructed with more accurate anthropometry data and refined meshes of elements with higher standard of meshing quality.

Different belt force limitation concepts are being compared under configurations with different crash severity. Dummy loads and kinematics are being evaluated. However, the human body model study is not completed at this point.

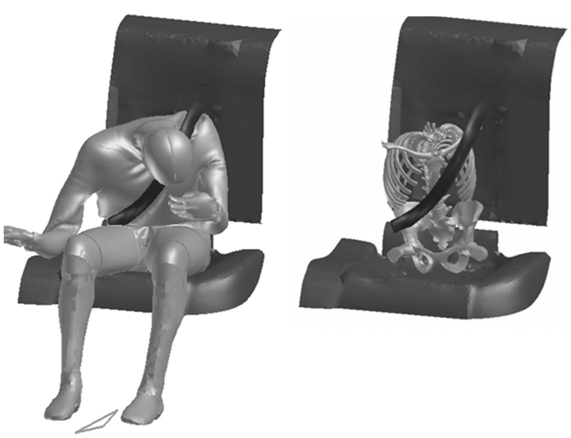

Figure15. Human body model motion with a 3 point belt.

First results indicate a change of the occupant kinematics and the peak loads level compared to 50th percentile hybrid III in particular with high crash pulse severity. Figure 15 shows the forward motion and deformation of the human body model's chest at 100 ms. The model tends to have a higher upper torso rotation around the Z axis when exposed to a full width flat wall crash configuration at 50 km/h with a seat belt with no pretension and no belt force limitation.

This might lead to a more selective assessment of the head contact risk with adapted belt force limitation concepts and advanced components in real accidents.

The started activities are intended to be continued in order to confirm the benefit of the countermeasures discussed before.

APPENDIX

Table1.
Injury reference values

Reference Values	5% female	50% male
HEAD		
HIC_{36}	**1000**	**1000**
res. acceleration (3 ms) [g]	**88**	**88**
NECK		
Tension force [kN[	**2,1**	**3,3**
Extension moment [Nm]	**49**	**57**
CHEST		
Compression [mm]	**41**	**50**
FEMUR		
Compression force [kN]	**6,0**	**9,07**

REFERENCES

[1] Schönebeck S., Schepers A., Pöppel-Decker M., Leipnitz C., Fitschen A.
Voraussichtliche Entwicklung von Unfallanzahlen und Jahresfahrleistungen in Deutschland, Ergebnisse 2011
Bundesanstalt für Straßenwesen

[2] Kuppa S., Saunders J., Fessahaie O.
Rear Seat Occupant Protection in Frontal Crashes
International Technical Conference of the Enhanced Safety of Vehicles, 2005

[3] Forman J., Michelson J., Kent R.; Kuppa S., Bostrom O.
Occupant Restraint in the Rear Seat: ATD Responses to Standard and Pre-Tensioning, Force –Limiting Belt Restraints
52^{nd} AAAM Conference, 2008

[4] Stegmeier M., Bausch H.
Rear Seat Protection for Occupants Sizes from Q6 to HIII 95%ile in Frontal Crashes
9^{th} International Conference Protection of Children in Cars, 2011

[5] Website China-NCAP
http://www.c-ncap.org.cn/C-NCAP/index.htm

[6] Website Japan-NCAP
http://www.nasva.go.jp/mamoru/en/index.html

[7] Website EuroNCAP
http://www.euroncap.com/home.aspx