Smart Safety restraint Systems: adapting to Real Crash Conditions for Improved Occupant Protection in Frontal Impact

Bo Shang, Xinchao Zhao, Wenhua Yuan, Dragos Codroiu, Darren Flett, Rong Zhang, Jianming Yan, Pan Zhang, Kehan Zhao, Pengyi Liu

I. INTRODUCTION

The traditional automotive restraint system (TRS) is designed primarily for specific high-speed crash conditions and as such may not offer the best protection for occupants in real-world crash scenarios [1-2]. Notably, most accidents occur at low to medium speeds, and in these scenarios, the excessive rigidity of current restraint systems places occupants at an increased risk of injury [3-9]. In addition, the diversity in occupant body shape and size and in seating positions during actual accidents is often not reflected in the design parameters of these systems, leading to potential gaps in real world crash protection. In a bid to enhance safety measures, Euro NCAP plans to implement a new test in 2026 [10] that will specifically assess vehicle performance in low to medium crash severity scenarios. This development highlights the need for a Smart Safety restraint System (SSS) that intelligently adjusts to the crash severity, the occupant’s type and the seating position to optimise protection.

This paper evaluates the effect of SSS on vehicle occupants in six crash scenarios using different anthropomorphic test devices (ATDs) and the Total Human Model for Safety (THUMS) human body model (HBM) representing various body types. Findings indicate SSS significantly reduces head and chest injury risks, especially in lower-speed impacts, and maintains protection in high-speed crashes.

II. METHODS

The effectiveness of SSS to protect occupants using Hybrid III, THOR-50M dummies, and the THUMS HBM in simulated crashes from 26 km/h to 64 km/h is investigated in this study. The configurations for both the TRS and the SSS are provided in Table AI. Advanced sensors (Table AII) in the base model enable the SSS to identify occupants of different sizes. The acceleration profiles, the shoulder belt force and the specific seat positions across occupants of different body sizes are illustrated in Figs A1, 2 and 3, respectively. The base model is validated through sled testing with THOR-50M ATD, presented in Fig. A4 and Fig. A5. The base model demonstrated good correlation with the test results.

To assess the effectiveness of the SSS, the injury values for the head, neck and chest, which are obtained from the ATD and HBM simulations, are transformed into Abbreviated Injury Scale (AIS) risk probabilities (Fig. A6) [11-15].

III. INITIAL FINDINGS

Results for the 5th, 50th and 95th percentile driver models are displayed in Figs. A7, 8 and 9, respectively. The presented values in the figures, which were obtained by calculating the difference in injury risk values between TRS and SSS, serve to illustrate the benefits of SSS across each injury criterion. Negative values were indicative of lower injury risks with SSS as compared to TRS, while positive values suggested higher risks.

For the 5th percentile driver, a consistent decrease in head (HIC15) and chest injury risks was observed across all crash scenarios. Additionally, a significant decrease in BrIC with SSS was noted during lower and middle-speed crash scenarios. However, in high-speed impact test conditions using ATD, SSS was associated with a higher BrIC risk (BrIC=0.69 in 64SORB). Nevertheless, for the THUMS, BrIC injury risk was found to be comparable across all impact conditions. Mixed results were presented for neck injury (Nij) risks, though a majority of test conditions indicated a lower injury risk with SSS. Furthermore, no risk of head strike-through was observed in this study.

For the 50th percentile driver, SSS consistently yielded a lower HIC15 and chest injury risk under all impact conditions. Nij was minimal for both TRS and SSS in all instances. Although BrIC injury risk was generally similar between TRS and SSS across most models, an increase in BrIC risk under SSS was noted in the 64SORB model,

B. Shang (e-mail: bo.shang@nio.com; tel: +86 187 2112 2995) is a Senior Staff engineer and X. Zhao is an Expert and Depart Manager in the Department of Vehicle Safety in NIO. W. Yuan and D. Flett are Experts, and D. Codroiu, R. Zhang, J. Yan, K. Zhao, P. Zhang and P. Liu are Staff engineers in NIO.

particularly for the THOR-50M dummy. No head strike-through risk was identified across all models.

For the 95th percentile driver, the SSS generally perform at a comparable level or better than the TRS in terms of head and neck injury risk. When it comes to chest injury, the SSS exhibits a similar risk in most scenarios, with the exceptions of the 56FF and 64ODB scenarios. In these cases, the injury risk values increased by 7.09% and 2.02%, respectively. The minimum distance between the head and the steering wheel for THUMS is 24mm in the 56FF with TRS. While for the ATD, the worst case occurred in 64SORB when using TRS, where the minimum distance is 14mm, which was close to the DAB bottoming out.

IV. DISCUSSION

For the 5th percentile driver, the seatbelt load limiter quickly adjusts to a lower force level in low and middle-speed crash conditions. Meanwhile, the DAB became softer as the active vent opened. The compatibility of the seatbelt with the DAB has achieved a reduction in the overall stiffness of the restraint system, which helped to restrain the occupant while minimising the load transferred to the thorax and head. As a result, the risks of head, neck, and chest injuries are lowered. However, during high-speed impacts, the combination of lower load limiter and softer DAB resulted in rapid head around the Y-axis, leading to a rise in the BrIC value when ATD was used. This increase was not evidently observed when the THUMS was used.

For the 50th percentile driver, the use of SSS was associated with a consistently lower risk of head and chest injuries under all impact conditions, despite an observed increase in BrIC injury risk under SSS in the 64SORB model for the THOR-50M dummy. Here, an increase in the BrIC value from 0.75 with TRS to 0.80 with SSS was noted. The restraint of the upper torso was found to be compromised by the delayed switch to a lower seatbelt load limiter when SSS was used. This allows for quicker rotation of the head about both the Y- and Z-axes when compared to TRS, resulting in an increased BrIC injury value for the THOR-50M dummy.

For the 95th percentile driver, the SSS generally presented a head and neck injury risk similar to that of TRS across all scenarios. However, a significant increase in chest injury risk in the 56FF scenario for the THUMS with SSS was observed. This is mainly attributed to a higher seatbelt load limiter being used with SSS, and the DAB was stiffer in SSS than in TRS. Additional, different kinematics of THUMS and ATD, generate an increased engagement with DAB and the thorax of THUMS, resulting in a raised load on the thorax.

The potential for reducing head and chest injury risks for drivers of various body types across multiple crash scenarios was demonstrated by the SSS. This reduction in risk is particularly evident in low and middle-speed impact scenarios. Although the SSS was generally found to be more effective than the TRS in many respects, it is acknowledged that there are specific areas performance of SSS that could be enhanced, especially during high-speed impacts and with certain percentiles of drivers. Therefore, it will be crucial to focus on optimising the SSS for high-speed impacts and on accommodating diverse driver populations.

The diverse outcomes and the reliance of results on specific models underscore the complexities of predicting injury risk and the need for further research in this area. Future efforts should focus on refining injury risk models and broadening the range of tests to encompass various crash scenarios. To ensure the practical relevance of these research findings, studies that validate using real-world crash data are recommended. Additionally, the precise recognition of the occupant's body type, the crash severity and the crash type, in other words, the robustness of SSS, also need to be evaluated. The ultimate aim is to contribute to the creation of more effective vehicle safety systems.

V. REFERENCES

[1] Brumbelow, M., *et al.*, IRCOBI, 2019.
[2] Huang, Y., *et al. Int J Vehicle Safety*, 2015.
[3] Östling, M., *et al.*, IRCOBI, 2023.
[4] Hynd, D., *et al.*, TRL, 2011.
[5] Ekambaram, K., *et al., J Traf Inj Prev*, 2019.
[6] Mertz, H., *et al.,* STAPP, 2007.
[7] Forman, J., *et al., J Traf Inj Prev*, 2018.
[8] Forman, J., *et al.,* ESV, 2023.
[9] Ekambaram, K., *et al., J Traf Inj Prev*, 2019.
[10] Ratingen, M., CARHS, 2022.
[11] NHTSA, NCAP, 2008.
[12] Craig, K., *et al*., NHTSA, 2020.
[13] Takhounts, *et al*., STAPP, 2013.
[14] Forman, J., *et al.,* IRCOBI, 2022.
[15] Takata, DOT HS 812 432, 2017.

VI. APPENDIX

TABLE AI

COMPARISON CONFIGURATION OF TRS AND SSS

	Seatbelt		*DAB*	
	Type	*Load limiter force level*	*Stage*	*Active vent (AVE)*
TRS	Constant load limiter (LLC) + Pyrotechnic Lap belt pretensioner (PLP)	49Nm	Single stage	NA
SSS	Adaptive load limiter (LLA) +PLP	63-27Nm	Dual stage	with

TABLE AII

ADVANCED SENSORS EQUIPPED IN BASE MODEL

STPS	Seat Track Position Sensor
OCS	Occupant Classification System sensor
DMS	Driver Monitoring Sensor
OMS	Occupant Monitoring Sensor

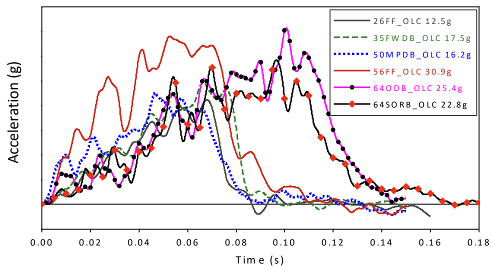

Fig. A1. Crash pules of six types of frontal impact scenario.

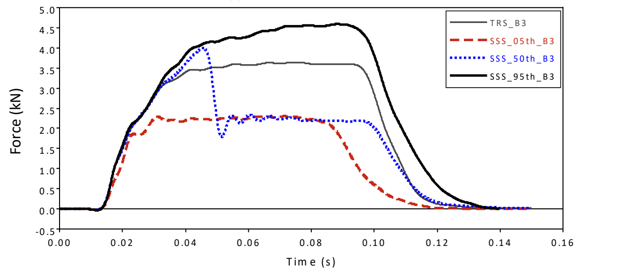

Fig. A2. Shoulder-belt force of SSS for occupants of different size.

Fig. A3. Seat positions for the 5th, 50th and 95th occupants.

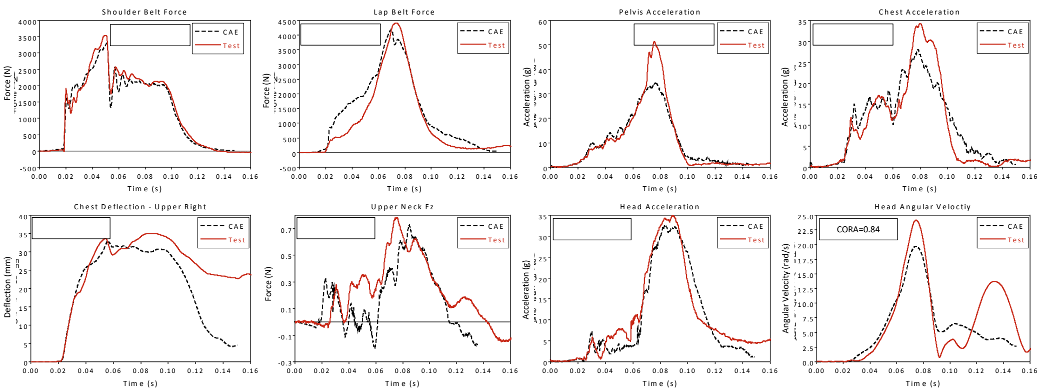

Fig. A4. Corresponding physical sled MPDB test and CAE simulation.

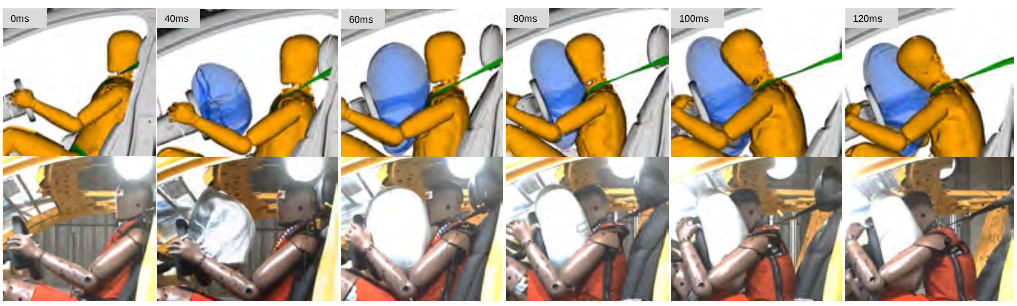

Fig. A5. Simulation (top) and frontal sled in the 50 km/h MPDB crash test (bottom).

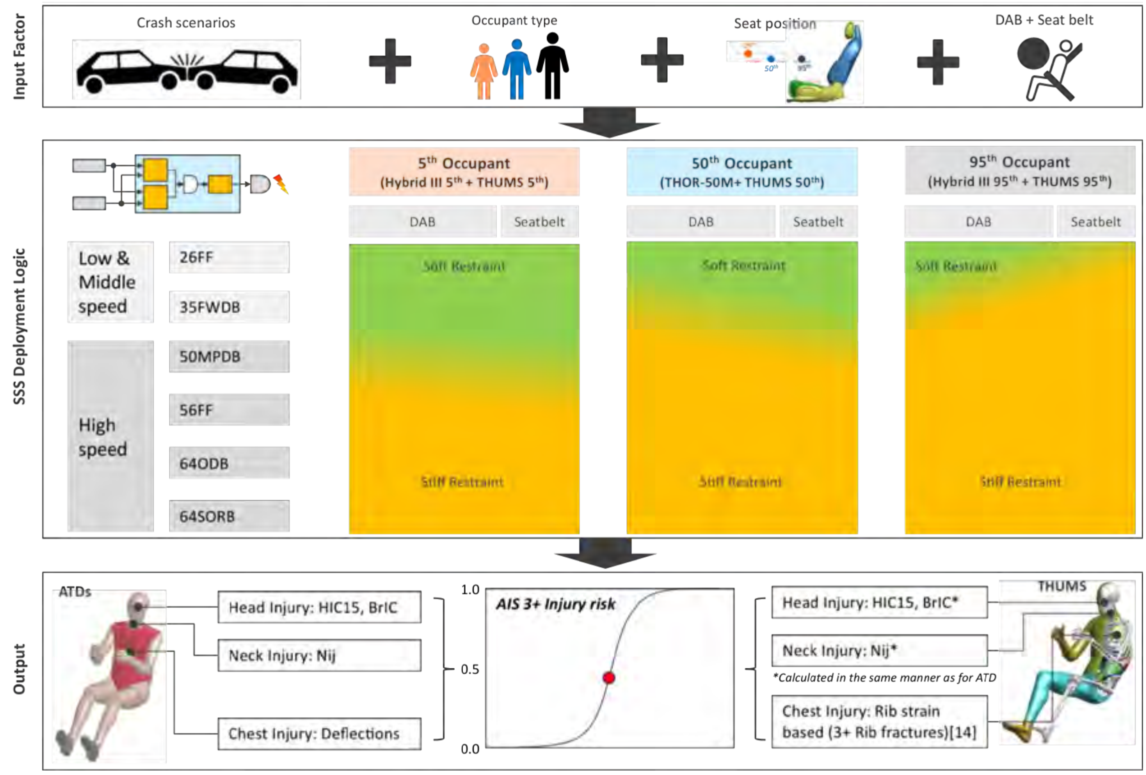

Fig. A6. Simulation based approach and assessment.

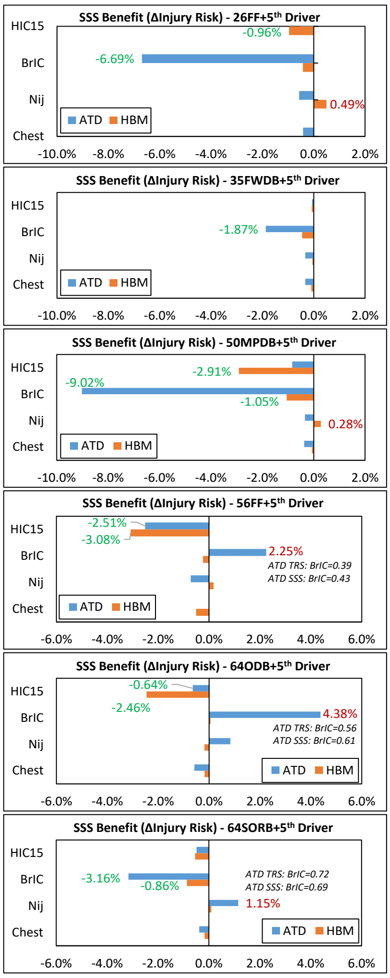

Fig. A7. SSS benefit for 5th occupant.

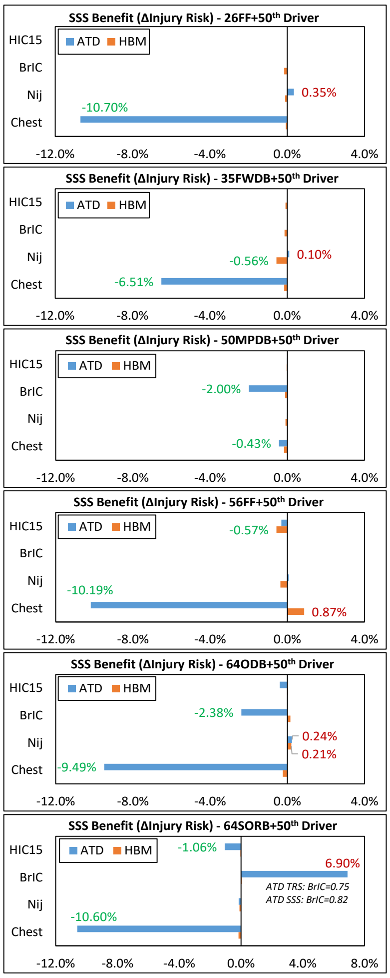

Fig. A8. SSS benefit for 50th occupant.

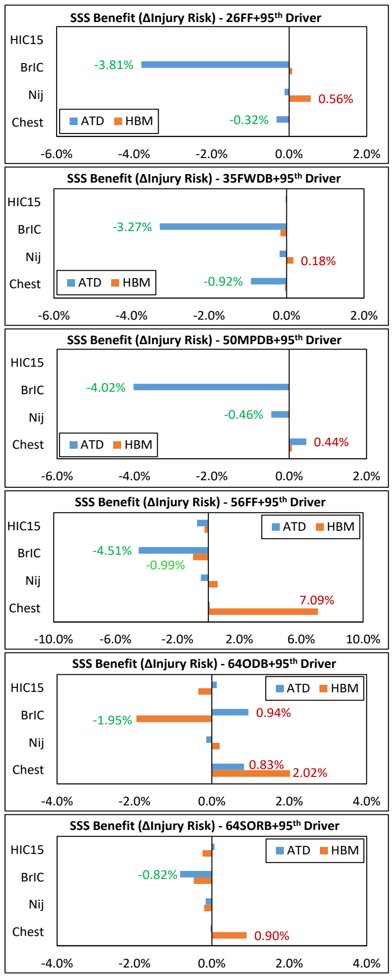

Fig. A9. SSS benefit for 95th occupant.