Occupant Injury Risk Assessment during a Car–to-End Terminal Crash under Crash Test Conditions and Extended Scenarios

Yunzhu Meng[1], Costin Untaroiu[1]
[1] Department of Biomedical Engineering and Mechanics
Virginia Tech, Blacksburg, VA, USA

Abstract

The safety performance of ET-Plus, the most common energy-absorbing guardrail end terminal used in the U.S., was evaluated based on the crash tests recommended by the National Cooperative Highway Research Program (NCHRP). However, while the NCHRP standards were updated to Manual for Assessing Safety Hardware (MASH) in 2009, the safety performance of ET-Plus was not re-evaluated by the updated tests. Also, the occupant injury was evaluated on the full-body level and no seatbelt or airbag usage was considered. Therefore, the main objectives of this study were to evaluate the safety performance of ET-Plus under the MASH test conditions and to assess occupant body-region injuries under varied impact conditions for the first time.

Yaris car to ET-Plus crashes simulations were developed based on two sets of MASH test conditions to evaluate the safety performance of ET-Plus. Furthermore, extended scenarios were developed in this study to evaluate the occupant injury risk in varied impact conditions. Three impact velocities (80, 100, and 120 km/h), two impact angles (0, and 15 degrees), and two impact overlap (none, and 25% passenger-side) were used as the pre-impact condition parameters. In each simulation, Occupant Impact Velocity (OIV) and Occupant Ridedown Acceleration (ORA) were calculated and compared to the body-region injury probabilities. The body-region injury probabilities were calculated based on the kinematic responses of the dummy head, neck, and chest. The injury potential was evaluated (HIC, Nij, maximum chest deflection, and chest acceleration) and the severe injury probabilities were then assessed for head and neck injury, and chest injury.

For the two simulations developed based on the MASH test conditions, the one with a small overlap (test 30) passes all the requirements while the other one (test 32) failed because the OIV longitudinal exceeds the threshold. Considering the extended scenarios, the average OIV longitudinal was observed to increase with pre-impact velocity: they were recorded as12.3, 12.6, and 14.0 m/s while the pre-impact velocity was 80, 100, and 120 km/h, respectively. Meanwhile, OIV longitudinal was observed to be a good predictor for chest injury while it cannot be used to predict head and neck injury. The OIV lateral was found to be correlated to the head and neck injury. However, it is not recommended to be used to do accurate predictions since the p-value is close to 0.05. On the other hand, the ORA, both longitudinal and lateral, were observed to have no predictability for either head and neck injury or chest injury.

This study indicated that the ET-Plus may have the weak capability to protect the occupant during a vehicle to end terminal collision because it would fail MASH test 32 based on the simulation results. Meanwhile, OIV and ORA were observed to have a low capability to predict occupant body-region injuries. Only the OIV longitudinal has predictability for chest injury probability. Head and neck injury, which is a common occupant injury, cannot be assessed by any vehicle-based metrics. Therefore, the usage of dummies should be recommended to the current test requirements. The numerical simulation methods could also supplement the development of new crash tests with varied impact conditions and the optimization of the design of guardrail end terminals.

Introduction

Guardrail is a designed part installed along U.S. roads to reduce crash severity by preventing the vehicle from going into off-road areas. However, the guardrail became a hazardous part because it caused 958 fatalities in 2017 in the U.S., which counted as 9% of all the fatalities involved in the collision with fixed-objects [1]. To evaluate the safety performance of guardrail end terminals, standard crash tests were performed based on either National Cooperative Highway Research Program (NCHRP) or Manual for Assessing Safety Hardware (MASH) guidelines. Since the MASH guideline was developed by updating the NCHRP guideline, several NCHRP-tested guardrail end terminals were not required to be tested under MASH conditions [2, 3]. Therefore, it is questionable if these end terminals have a proper safety performance under the MASH test conditions.

In both NCHRP and MASH crash tests, the occupant injury risk was evaluated based on vehicle kinematic responses. The occupant was assumed to be a mass point during the crash, so only full-body injury was assessed. Meanwhile, the evaluation methods used in testing does not consider the usage of seatbelt or airbag [4]. While the airbags and seatbelts are commonly used in current vehicles, Anthropomorphic Test Dummy (ATD) was introduced into varied crash tests [5-7]. With the employed ATD, the occupant full-body injury risk could be evaluated more accurately by accumulating body-region injury probabilities [8, 9].

With recent updates in the computational simulation methods, Finite Element (FE) simulations became an efficient alternative and a supportive method to crash tests. A previous ET-Plus model was developed and validated based on NCHRP test data [10]. Several dummy and vehicle models were previously developed and used in varied crash conditions [11-13]. However, no study was performed to integrate these models and assess occupant injury probability in a car-to-end terminal crash.

The main objectives of this study were to evaluate the safety performance of ET-Plus under the MASH test conditions and to assess occupant body-region injuries under varied impact conditions for the first time. Specifically, computational simulations were developed to model vehicle-to-ET-Plus crashes using LS-DYNA® software (LSTC, Livermore, CA). The safety performances of ET-Plus were evaluated based on the MASH criteria and the occupant injury probabilities were assessed based on dummy kinematic responses. Statistical correlations were then performed to evaluate the predictability of current safety evaluation methods used in NCHRP/MASH guidelines.

Methods

Several vehicle-to-ET-Plus crash FE simulations were performed in LS-DYNA software to evaluate the safety performance of ET-Plus under MASH conditions. A previously-developed and validated ET-Plus model was used in this study [10]. The model has an installment height as 27 ¾ inches. Although both wood and steel material can be used for the posts, only wood material properties were used in the simulations. To confirm the requirements of 1100C vehicles in the MASH guidelines, a previously published Toyota Yaris vehicle model was used in the simulations (Figure 1) [2, 14, 15]. The vehicle model has a weight of 1100 kg. Most of the vehicle interior parts, except seatbelt and airbag, were fully modeled. Thus, the models of these passenger safety restraint systems were added to the original vehicle model in this study. The material and geometric parameters were collected from the previously-published model [16, 17]. Although a dummy was not required in the MASH tests, a Hybrid III occupant dummy (50th percentile) was assigned on the driver seat to qualitatively assess injury probabilities (Figure 1). Head, neck, and chest injuries were assessed because they are observed to be the most critical occupant injuries in motor vehicle crashes [18]. During crash simulations, the time histories of head acceleration were recorded to calculate the HIC value. The neck force and moment were recorded to estimate neck injuries using Nij. In addition, chest acceleration, and chest deflections were recorded in the simulations corresponding to chest injuries.

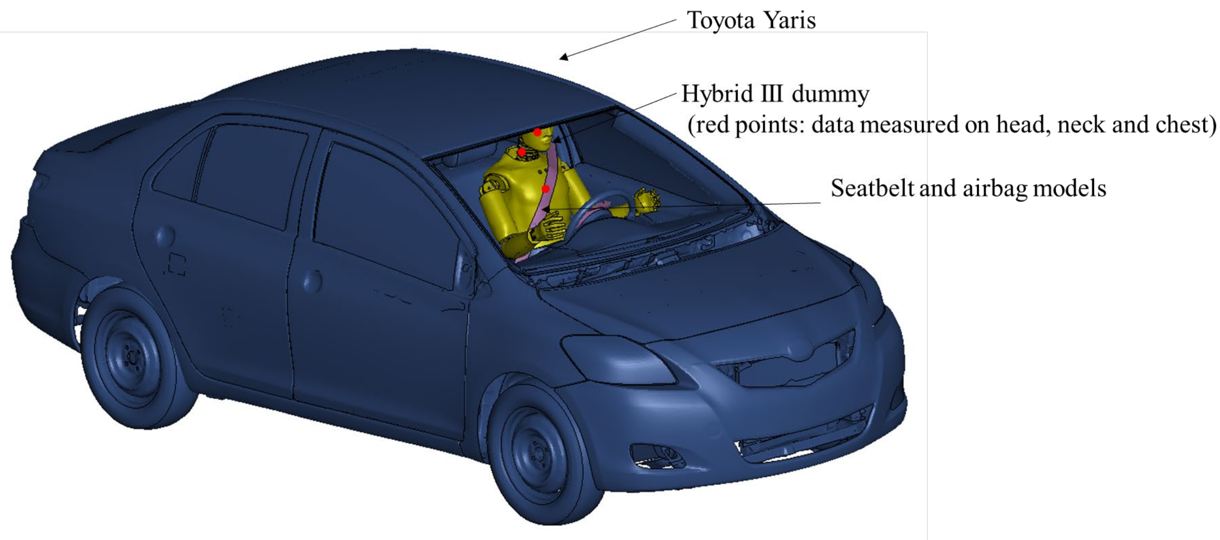

Figure 1. Vehicle and dummy model

Vehicle-to-end terminal crashes were simulated using MASH crash conditions. The simulations were developed under the conditions of test 30 and 32 (Figure 2a, b). In both simulations, the pre-impact velocities were 100 km/h (62 mph). One simulation was performed to simulate a passenger-side 25% overlap crash while the vehicle was parallel to the guardrail (same as test 30). The other simulation was developed to simulate a frontal crash while the angle between vehicle and barrier is 15° and the vehicle was impacted in the middle of the bumper (same as test 32).

In addition to the standard crash scenarios, extra crash simulations were performed in this study. Two extra pre-impact velocities were assigned to the vehicle model (80 and 120 km/h). Two extra scenarios were also developed. In one scenario, the pre-impact angles were assigned as 0 and the vehicle impacted the end terminal in the middle of the front bumper (Figure 2c). In another scenario, the pre-impact angle was assigned as 15° and a 25% passenger-side overlap was defined as the impact conditions (Figure 2d). In all the simulations, the vehicle responses were recorded at the center of gravity (CG) of the vehicle. The time histories of acceleration were used to evaluate occupant safety based on the flail-space model, which is required in the MASH guideline.

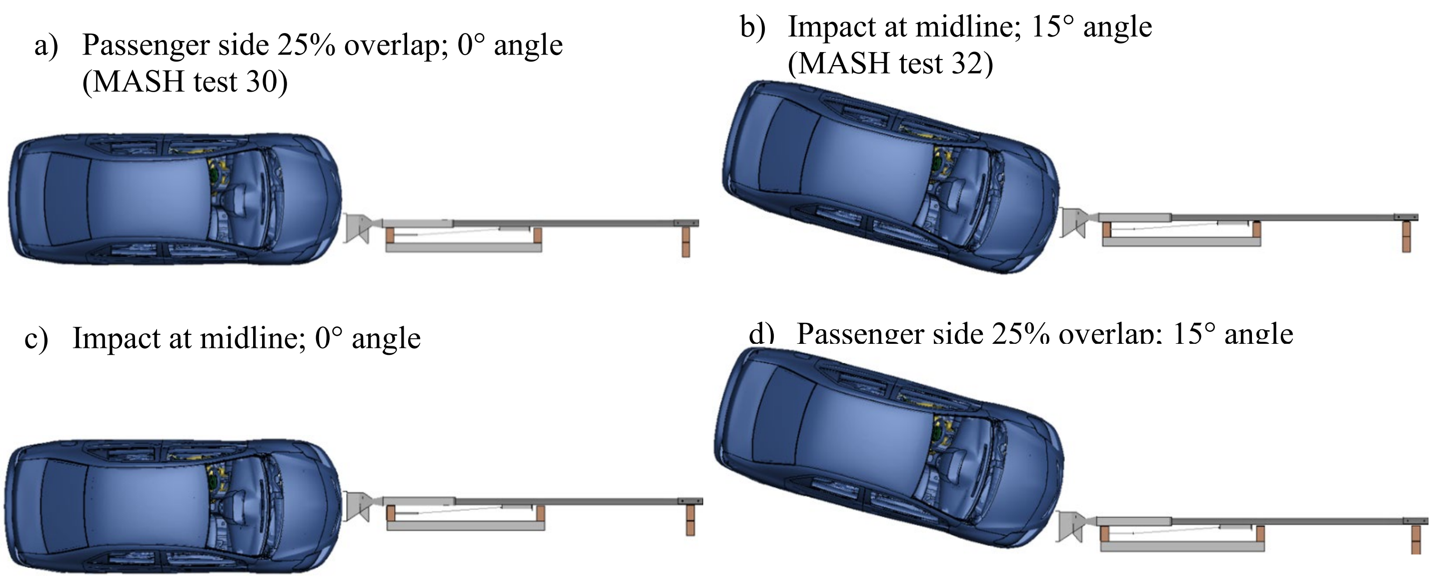

Figure 2. Crash scenarios

Occupant risk was evaluated based on several vehicle-based criteria according to the MASH guideline. First, there should be no penetration between vehicle and guardrail end terminal models. Second, the max roll and pitch angle should not exceed 75°. Third, the Occupant Impact Velocity (OIV) and Occupant Ridedown Acceleration (ORA) should satisfy the limits that OIV ≤ 12.2 m/s and ORA ≤ 20.49g. While all these criteria were checked in the simulations, extra qualitative occupant injury probabilities were calculated in this study. Head injury criteria (HIC_{15}), neck injury criteria (Nij), chest acceleration (As), and chest deformation (ChestDef) were calculated and compared to FMVSS 208 criteria (Table 1).

Table 1. Dummy injury assessments limits

HIC15	Nij	As (g)	ChestDef (mm)
700	1	60	63

The head, neck, and chest injury probabilities were then assessed based on the following equations (Eq. 1,2, 4) [9]. Considering the Abbreviated Injury Scale (AIS), the head and neck injury probabilities were merged (Eq. 3) [19]. Linear regression was performed to investigate the predictability of OIV and ORA for occupant injury probabilities. The regression curve was shown in Eq. 5. The p-value of *a* was then investigated to check if the regression is statistically confident. If the p-value is less than 0.05, then the MASH criterion was considered to have predictability to the injury.

$$P(Head) = \Phi(\frac{\ln(HIC_{15})-7.45231}{0.73998}) \quad (1)$$

$$P(Neck) = \frac{1}{1+e^{3.227-1.969\times N_{ij}}} \quad (2)$$

$$P(Head\ and\ Neck) = 1-(1-P(Head))\times(1-P(Neck)) \quad (3)$$

$$P(Chest) = \frac{1}{1+e^{3.1493-0.063\times As}} \quad (4)$$

$$\log(P(injury)) = a * MASH\ crierion + b \quad (5)$$

Results

Both simulations, which were developed based on the MASH test conditions, were normally terminated. The vehicle models were redirected to the traffic side of the guardrail, no penetration between the vehicle and the guardrail was observed in the simulations. The vehicle model kept upright during the crashes with a pitch and roll angle less than 75° which under the MASH thresholds. The OIV and ORA were calculated based on each simulation (Table 1). Overall, the vehicle-to-ET-Plus crash with a small overlap (test 30, simulation No. 5) passes the requirements while the other one (test 32, simulation No. 8) failed because the OIV longitudinal exceeds the threshold.

All the other simulations were also normally terminated. All the vehicle models were observed to be smoothly redirected after the impact with the end terminal model. The OIV and ORA were calculated and listed in Table 1. Comparing to the MASH limits, low injury probability was observed in the 25% passenger-side overlap crashes with a pre-impact velocity as 80 and 100 km/h (simulation No. 1, 2, 5, and 6). The OIV and ORA longitudinal were commonly observed to be larger than the OIV and ORA lateral, respectively. Overall, the majority of the simulations (8 out of 12) have an OIV longitudinal which is larger than the MASH limit (12.2 m/s) while all the OIV lateral are under the limit. The average OIV longitudinal was observed to increase with pre-impact velocity: they were recorded as12.3, 12.6, and 14.0 m/s while the pre-impact velocity was 80, 100, and 120 km/h, respectively. Furthermore, only two of the simulations have a large ORA longitudinal (> 20.49 g).

Both of the simulations occurred while the impact angle is 0° and the impact point is the middle of the bumper (Figure 2c). Meanwhile, all the ORA lateral were observed to be under the limits.

Table 1. Occupant risk evaluations based on MASH

No.	Pre-impact vehicle conditions			Occupant risk evaluation values			
	Velocity (km/h)	Overlap	Angle (°)	OIVx (m/s)	OIVy (m/s)	ORAx (g)	ORAy (g)
1	80	25%	0	12.1	0.2	12.28	3.67
2	80	25%	15	11.3	2.7	3.72	4.86
3	80	0	0	**12.7**	0.5	12.88	2.87
4	80	0	15	**13.2**	2.7	11.72	5.25
5	100	25%	0	11.9	0.2	19.60	7.10
6	100	25%	15	12.0	2.6	6.32	8.51
7	100	0	0	**13.0**	0.6	**25.30**	7.01
8	100	0	15	**13.4**	2.5	12.18	7.77
9	120	25%	0	**12.6**	0.3	19.50	7.94
10	120	25%	15	**13.1**	3.0	9.22	16.78
11	120	0	0	**16.2**	0.6	**22.86**	9.21
12	120	0	15	**14.2**	2.8	6.47	5.13
			MASH limits	12.2	12.2	20.49	20.49

Note: OIVx: OIV longitudinal
OIVy: OIV lateral
ORAx: ORA longitudinal
ORAy: ORA lateral

All the values of dummy injury criteria were observed to be less than the FMVSS 208 limits (Table 2). The body-region injury probabilities were observed to increase with increasing pre-impact vehicle velocity. For the crashes with an 80, 100, and 120 km/h pre-impact velocity, the average head and neck injury probabilities were observed to be 7.7%, 10.9%, and 14.2%, and the average chest injury probabilities were observed to be 1.9%, 4.4%, and 12.2%, respectively (Table 2).

Table 2. Dummy injury assessments

Pre-impact vehicle conditions			Occupant risk criteria				Occupant injury probabilities	
Velocity (km/h)	Overlap	Angle (°)	HIC15	Nij	As (g)	ChestDef (mm)	Head and Neck (%)	Chest (%)
80	25%	0	88	0.15	21	20	5.0	1.5
80	25%	15	219	0.69	22	15	13.6	1.2
80	0	0	155	0.19	24	24	5.5	2.6
80	0	15	69	0.31	26	22	6.8	2.4
100	25%	0	50	0.41	21	27	8.2	2.4
100	25%	15	308	0.52	24	23	10.9	2.4
100	0	0	465	0.55	31	29	13.9	6.1
100	0	15	133	0.56	33	29	10.7	6.7
120	25%	0	99	0.16	22	29	5.2	2.9
120	25%	15	481	0.73	24	22	17.8	2.1
120	0	0	351	0.65	48	39	13.9	31.5
120	0	15	397	0.86	38	32	19.8	12.1
		Limits	700	1	60	63		

OIV longitudinal was observed to be a good predictor for chest injury while it cannot be used to predict head and neck injury (Figure 3a). The OIV lateral was found to be correlated to the head and neck injury (Figure 3b). However, it should be noted that it is not recommended to be used to do accurate predictions since the p-value is close to 0.05. Meanwhile, the ORA, both longitudinal and lateral, were observed to have no predictability for either head and neck injury or chest injury (Figure 3c). It should be also mentioned that no regression curve can be found for OIV lateral vs. chest injury and ORA longitudinal vs. head and neck injury. A negative *a* value was found for these relationships which is unrealistic considering the physical meaning. Specifically, the occupant injury probability was expected to increase with the increasing occupant ridedown acceleration which requires the *a* to be a positive value.

Table 3. Dummy injury assessments

Vehicle based metrics	Injury	a	b	p-value of a
OIV longitudinal	Head and Neck	0.06	-1.77	0.248
	Chest	0.29	-5.19	**<.0001**
OIV lateral	Head and Neck	0.10	-1.16	**0.047**
	Chest		NA	
ORA longitudinal	Head and Neck		NA	
	Chest	0.03	-1.78	0.154
ORA lateral	Head and Neck	0.03	-1.21	0.105
	Chest	0.01	-1.52	0.747
Limits				0.05

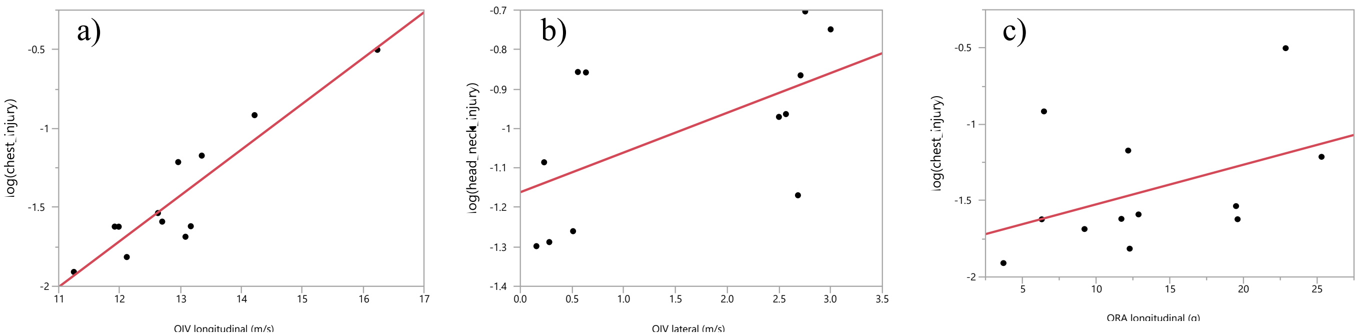

Figure 3. Regression curves for vehicle safety performance and occupant body-region injury probabilities: a) OIV longitudinal vs. chest injury (p-value <0.0001); b) OIV lateral vs. head and neck injury (p-value = 0.047); c) ORA longitudinal vs. chest injury (p-value = 0.154)

Discussion and Conclusion

For the first time, this study evaluated numerically the safety performance of ET-Plus under the MASH test conditions and to assess occupant body-region injuries under varied impact conditions. It pointed out some limitations of the current safety evaluation methods used for end terminals. The NCHRP-tested end terminal may fail the MASH tests. In particular, while the ET-Plus was observed to have good safety performance under NCHRP350 test conditions, it was observed to fail MASH test 32 based on the simulation results from this study. These results indicated that the ET-Plus may have the weak capability to protect the occupant during a vehicle to end terminal collision. Therefore, crash tests would be recommended to be performed based on the MASH guideline in the future to evaluate the safety performance of ET-Plus.

On the other hand, the injury assessed by the MASH standards were observed to be more conservative than the one assessed by the FMVSS 208 limits. Most of the crashes (8 out of 12) simulated in this study show that it failed the MASH limits while all the crashes pass the FMVSS 208 limits. Meanwhile, OIV and ORA were observed to have a low capability to predict occupant body-region injuries. Only the OIV longitudinal has predictability for chest injury probability. Head and neck injury, which is a common occupant injury, cannot be assessed by any vehicle-based metrics. Therefore, the usage of dummies should be recommended to the current test requirements, the numerical simulation methods shown in this study can be used as a supplement for the current injury evaluation methods based on tests. This simulation method could also supplement the development of new crash tests with varied impact conditions and the optimization of the design of guardrail end terminals.

References

1. IIHS, *Fatality Facts 2018 Collisions with fixed objects and animals.* Arlington, VA, 2019.
2. AASHTO, *Manual for assessing safety hardware (MASH).* Washington, DC, 2009.
3. Welborn, C. *MASH Guardrail Implementation and Design*. in *MDT Preconstruction Conference*. 2018. Montana.
4. Michie, J.D., *Collision Risk Assessment Based on Occupant Flail Space Model*. 1981: The Institute.
5. Jin, H., et al., *Evaluation of the Injury Risks of Truck Occupants Involved in a Crash as a Result of Errant Truck Platoons.* 2018.
6. Li, N., et al., *A numerical study of occupant responses and injuries in vehicular crashes into roadside barriers based on finite element simulations.* Advances in Engineering Software, 2015. **90**: p. 22-40.
7. Seyedi, M., et al., *Experimental and Numerical Analysis of Injury Risk in Cutaway Bus Side Impact Test.*
8. Weaver, A.A., et al., *Estimated injury risk for specific injuries and body regions in frontal motor vehicle crashes.* 2015. **16**(sup1): p. S108-S116.
9. Eppinger, R., et al., *Development of improved injury criteria for the assessment of advanced automotive restraint systems.* 1998.
10. Meng, Y., W. Hu, and C. Untaroiu, *Finite Element Modeling of an Energy-Absorbing Guardrail End Terminal.* SAE International Journal of Commercial Vehicles, 2019. **12**(4).
11. Kan, C.-D., et al., *Crashworthiness evaluation using integrated vehicle and occupant finite element models.* 2001. **6**(3): p. 387-398.
12. Li, N., et al., *A numerical study of occupant responses and injuries in vehicular crashes into roadside barriers based on finite element simulations.* 2015. **90**: p. 22-40.
13. Marzougui, D., et al., *Extended validation of the finite element model for the 2010 Toyota Yaris Passenger Sedan.* 2012.
14. Marzougui, D., et al. *Development & Validation of a Finite Element Model for a Mid-Sized Passenger Sedan*. in *13th International LS-DYNA Users Conference*. 2014.
15. Marzougui, D., et al., *Extended validation of the finite element model for the 2010 Toyota Yaris Passenger Sedan.* National Crash Analysis Center, George Washington University, Washington, DC, Report No. NCAC, 2012.
16. Guha, S. *Occupant modeling workshops & other learning aids*. 2010 [cited 2020 01/29]; Available from: http://www.lstc.com/training_workshops.
17. Masiá, J., B. Eixerés, and J. Dols, *Models for airbag simulation in vehicles adapted for disabled drivers.* Zaragoza, 2008.
18. Wyatt, J., et al., *Injury analyses of fatal motorcycle collisions in south-east Scotland.* 1999. **104**(2-3): p. 127-132.
19. Gennarelli, T.A. and E. Wodzin, *AIS 2005: a contemporary injury scale.* Injury, 2006. **37**(12): p. 1083-1091.