ANALYSIS AND SIMULATION OF OCCUPANT INJURY RISK AT NASS/CDS

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ABSTRACT

The body regional injury information from the head, thorax, abdomen, upper and lower extremities of vehicle occupant due to the restraints and interior parts were extracted from 2009-2012 NASS/CDS data base. For those cases with high occurrence frequency, detailed and comprehensive data analysis was performed to find significances between the accident, occupant, vehicle, and injury data. A numerical frontal impact sled model with Hybrid III dummy and GHBMC human body model is constructed to simulate and identify those injury risks at NASS/CDS.
Among the 5,734 body regional injuries from frontal crash accidents, lower extremity (27.8%), upper extremity (21.3%), thorax (15.1%), face (10.9%), spine (8,7%), head (7.3%), and abdomen (6.9%) were found in order of frequent occurrence. The main injury sources of the head were windshield, side structure, and steering wheel. For thorax and abdomen, they were seat belt and steering wheel. Instrument panel was for the lower extremity. Body regional injury patterns for head were concussion and contusion. For thorax, they were vessel laceration and lung contusion. For abdomen, laceration and contusion of organs were major injury patterns. Bone fracture and ligament rupture were found at the lower extremity. Steering wheel and seat positions were main factors affect head and thorax injury risks. From the sled impact simulation, high injury risks of the head and thorax were assessed respectively at conditions of steering column tilt down and rear most seat positions, which correlated well with the findings at NASS/CDS data analysis.

INTRODUCTION

Occupant injury rate at crash accidents has not been decreased in proportion to the advancing vehicle safety technology and design. Crash injury occurs occasionally by restraint system, i.e., seat belt and airbag. When seat belt excessively restraints the occupant, it may bring rib fractures and abdominal organ ruptures. In the opposite case, the insufficient restraining would allow second impact and consequent injuries, i.e., from the impact of occupant against interior parts. Airbag can be a life threatening device when it becomes an injury source at a relatively lower speed crash. This study focuses on identifying injury sources of anatomical body regions of vehicle occupant and associated vehicle parameters. The representative scenarios of occupant's crash injury are also developed for the reconstruction of the injury risk with a numerical simulation that can further elucidates the outcomes of the study.
Pintar et al. [1] reported that the head injury risk became the least when both airbag and seat belt were used together. The multiple injuries at brain and skull are the most frequent head injury for those unbelted occupant with deployed airbag. Wallies and Greaves [2] presented that the airbag induced injury tended to increase with more airbag in use (i.e., deployed). The risk of skull fracture reduced by 42% due to the airbag [3], whereas the brain injury risk rather increased [4]. The increasing facial fracture risk by airbag at front seat passengers was reported by Murphy et al. [5]

The study of eye injury by airbag was done by Duma et al. [6] The growth of minor head injury (AIS 1) risk by the depowered airbag was analyzed by Huber et al. [7] Cerebrovascular injuries due to the airbag deployment were reported by Davis et al. [8]

Untatoiu et al. [9] has investigated the biomechanical response and injury outcome to the abdominal regions in static deployment tests using two pre-tensioner systems. The high belt (pre-tensioning) forces may increase the risk of abdominal injuries to the vehicle occupant since abdominal injuries (spleen lacerations) were observed in two PMHS with higher BMI. Using the whole lower limb FE model, sensitivity study was performed by Yue et al. [10] to evaluate the effect of the hip joint angle (occupant posture variation) to acetabulum injury tolerance in frontal impact. They reported the tolerance of the hip acetabulum (cortical bone) showed greater sensitivity to the hip extension angle than to the abduction angle.

Bostrom and Kruse [11] proposed a cost effective method of sled test to assess a head injury risk at small overlap crash. They found the dominating head injury mechanisms were head impact at interior part, i.e., A-pillar or at the external objects. It was also reported that the THOR dummy was an appropriate surrogate for the small overlap test while the Hybrid III was not.

The body regional AIS3+ (or 2+) injury information along head, thorax, abdomen, upper and lower extremities due to the restraints (airbag and seat belt) and interior parts (instrument panel, steering wheel, windshield, and etc.) were extracted from 2009-2012 NASS (National Automotive Sampling System)/CDS (Crashworthiness Data System) data base. The data were limited to the frontal crash (10-2 O'clock direction), driver and front seat passenger, and adult. And thus this filtering reduced the total number of injuries in the analysis from 17,915 to 5,734. For those cases with high occurrence frequency, detailed and comprehensive analysis was performed for accident (vehicle and accident types, vehicle speed), occupant (gender, height, weight, and position), vehicle (vehicle size and restraints), and injury (body region, type, and AIS) data.

Numerical frontal impact sled models with Hybrid III dummy and GHBMC(Global Human Body Models Consortium [12]) human body model were constructed to simulate and identify those injury risks at NASS/CDS data. The numerical injury simulations were proceeded in two steps. In the first step, the frontal crash sled simulation was performed with Hybrid III dummy to predict overall kinematics of the driver. In the following step, the same frontal crash sled model used at the first step applied but the driver model was substituted with anatomically detailed human body model, i.e., GHBMC model for more biomechanical injury prediction. The relatively simple composition of Hybrid III finite element dummy model (about 5k elements) in the first step facilitated more comprehensive parametric analysis while the second step with GHBMC human body model (about 2 million elements) was focused for few selected cases due to the heavy computational load.

Among the 5,734 body regional injuries from frontal crash accidents, lower extremity (27.8%), upper extremity (21.3%), thorax (15.1%), face (10.9%), spine (8,7%), head (7.3%), and abdomen (6.9%) were found in order of frequent occurrence. The main injury sources of the head were windshield, side structure, and steering wheel. For thorax and abdomen, they were seat belt and steering wheel. Instrument panel was for the lower extremity. Body regional injury (AIS 2+) patterns of head were concussion and contusion. For thorax, they were vessel laceration and lung contusion. For abdomen, laceration and contusion of organs were major injury patterns. Bone fracture and ligament rupture were found at the lower extremity. From the sled impact simulation, high injury risks of the head and thorax were assessed at conditions of steering wheel down and rear most seat position, respectively.

METHOD

Analysis of Parameters Effecting on Injury Risk

Using NASS/CDS database of 2009-2012, the frequency analysis of injury risk was performed along the anatomical body regions, i.e., head, face, neck, thorax, abdomen, spine, upper extremity, lower extremity, and unspecified. The injury types, organs in each body region were subsequently analyzed. The injury source such as instrument panel, steering wheel, windshield, airbag, seat belt, and etc. was also identified for those injuries with high levels (AIS 2 or 3+). Lastly, the detailed investigation to find a correlation of injury risk with other

parameters, i.e., accident type, vehicle closing speed, Delta V, occupant gender, age, and anthropometry, restraining condition, vehicle size, seat position, and steering column tilt angle were further carried out. Figure 1 shows the procedure of injury risk analysis in this study.

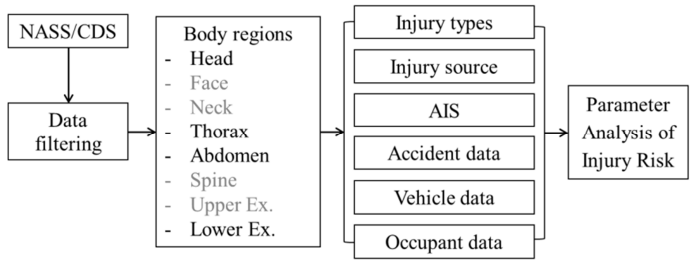


Figure 1. Procedure of injury risk analysis at NASS/CDS.

Numerical Simulation Model to Reconstruct Injury Risk

In order to verify the analyzed result of injury risk at NASS/CDS, numerical simulation using frontal impact sled model consists of driver side vehicle compartment including an aribag and seat belt were performed. Modeling parameters for airbag and seat belt such as mass flow rate, pretensioner and load limiter were calibrated against a medium sedan. Dummy kinematics such as head and chest accelerations and the belt force were validated against US NCAP test result of the target vehicle. Sled pulses at 56, 68, and 79 kph closing speed at a frontal crash were emulated to represent 25G, 30G, and 35G of vehicle peak decelerations, respectively. However, this sled model was only validated for upper body kinematics of driver due to the limited for the evaluation of head and thorax injury risks but none at lower extremity.

There were four main parameters in the sled simulation: 1. three restraining conditions, i.e., with/without airbag deployment and belted/unbelted (no case of unbelted without airbag deployment), 2. two seat positions, i.e., center and rear most, 3. three steering column tilt angles, i.e., -3/0/3 degrees, and 4. three impact speeds, i.e., 56, 68, and 79 kph. The modeling of the occupant restraining by airbag and seat belt, e.g., firing time, vent hole size, pretensioner, limit load, and etc. were identically applied to all simulation cases.

There were two kinds of occupant models (Figure 2) adopted in the sled simulation to respectively predict overall kinematics and biomechanical injury of driver at frontal crash. As a first analysis in two-step procedure of sled simulations, Hybrid III medium size male dummy model was used for predicting overall occupant kinematics and interactions with vehicle interior and restraints. The preliminary injury risk was assessed by quantifying the contact forces on various vehicle interior such as windshield, steering wheel against head and chest and HIC and amount of chest deflection at the Hybrid III dummy model. The effects of simulation parameters on injury risk were correlated with the result from data analysis of NASS/CDS. The GHBMC human body model with medium male size was also adopted to predict more biomechanical injury such as number of rib fractures for the thorax injury risk. No assessment of skull fracture, brain injury, abdomen organ rupture were included in the current study and it remains as on-going and future study.

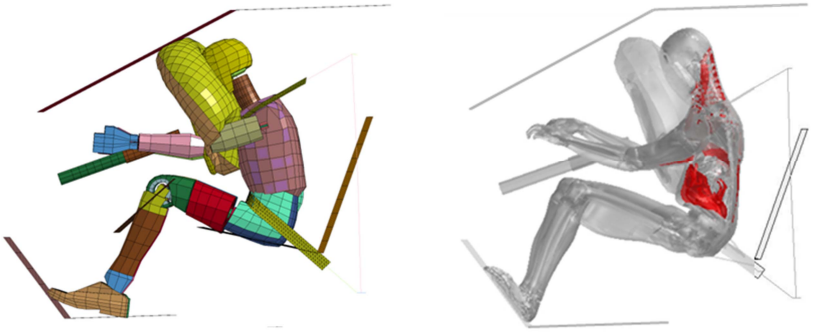


Figure 2. Frontal impact sled model with Hybrid III model (left) and GHBMC human body model (right).

RESULTS

Frequency Analysis of Body Regional Injury Risk

The body regional injury risk at frontal crash from 2009-12 NASS/CDS data is listed in Table 1. Among 5,734 injuries which is limited to adult driver and front seat passenger, lower extremity was the most frequent body region (27.8%) followed by upper extremity (21.3%), thorax (15.1%), face (10.9%), spine (8.7%), head (7.3%), abdomen (6.9%), and neck (1.3%).

Table 1. Body regional injury risk from 2009-2012 NASS/CDS.

Body regions	Injury frequency	Ratio (%)
Head	419	7.3
Face	627	10.9
Neck	74	1.3
Thorax	865	15.1
Abdomen	396	6.9
Spine	501	8.7
Upper Extremity	1,222	21.3
Lower Extremity	1,595	27.8
Unspecified	35	0.6
Total	5,734	100.0

Other than four main body regions (head, thorax, abdomen, and lower extremity), face, neck, spine, and upper extremity were not included at the further detailed analysis due to the relatively lower injury severity (AIS 2-) even with high occurrence rates.

The major injury sources and associated injury patterns of head are investigated (Table 2). Top three head injury sources, i.e., windshield, side structure, and steering wheel showed a similar occurrence rate. The most significant factor with the windshield became airbag and unbelted condition, especially for AIS 3+ head injury (90%, 9 out of 10 cases). The full down position of steering column was also an effective variable (80%, 4 out of 5 cases). In case of side structure to head injury risk, airbag and belted (66%, 19 out of 29 cases of AIS 3+ head injury) and rear most seat position (57%, 13 out of 23 cases) were dominant variables. Unbelted (58%, 18 out of 31 cases of AIS 3+ head injury) and full up steering column position (69%, 11 out of 16 cases) were prominent factors with steering wheel. For instrument panel, the controlling variables are airbag and belted (52%, 13 out of 25 cases of AIS 3+ head injury) and rear most seat position (65%, 15 out of 23 cases). The airbag as head injury source was affected by age and gender but quantitative analysis was not feasible. Figure 3 shows an example NASS/CDS case (2009-73-074) of head injury due to the steering wheel.

Table 2. Head injury source and pattern.

Injury source	Injury freque	Ratio (%)	Major lesion	Restraint	Injury variable
Windshield	74	17.7	Contusion*	Airbag & Unbelted	Steering column position (full down)
Side structure	67	16.0	Contusion*	Airbag & Belted	Occupant position (rear most)
Steering wheel	66	15.8	Contusion*	Unbelted	Steering column position (full up)
Instrument panel	40	9.5	Concussion**	Airbag	Occupant position (rear most)
Airbag	26	6.2	Concussion**	Airbag & Belted	Occupant age and sex (old and female)
Etc.	146	34.8	-	-	-
Total	419	100	-	-	-

* Contusion: 27.2% of head injuries

** Concussion: 25.1% of head injuries

Figure 3. NASS/CDS case (2009-79-074) of head injury due to the steering wheel: unbelted driver, Delta V 46 kph, Head AIS 5, ISS 30.

The results of thorax injury with major sources and associated patterns are summarized in Table 3. The belt web was the most frequent injury source (62%) to the thorax of which airbag was deployed for all AIS 3+ injuries (100%, 28 out of 28 cases). And the rear most seat position was another dominant variable (82%, 14 out of 17 cases). In case of steering wheel, airbag and unbelted was the most common restraining condition for AIS 4+ injury level (71%, 24 out 30 cases) and the upright seat back angle was also marked a variable (52%, 12 out of 23 cases). For instrument panel, the controlling variables are airbag and belted (92%, 11 out of 12 cases of AIS 4+ thorax injury) and rear most seat position (82%, 9 out of 11 cases). The quantitative analysis for inner trim, seat back, and airbag as injury source was not feasible. Figure 4 shows an example NASS/CDS case (2010-79-070) of thorax injury due to the belt web.

Table 3. Injury pattern and source of thorax.

Injury source	Injury frequency	Ratio (%)	Major lesion	Restraint	Injury variable
Belt web	538	62.2	Laceration*, Fracture**	Airbag & Belted	Occupant position (rear most)
Steering wheel	176	20.3	Laceration*	Airbag & Unbelted	Occupant posture (seat back angle)
Instrument panel	55	6.4	Laceration*, Contusion#	Airbag & Unbelted	Occupant position (rear most)
Inner trim	47	5.4	Laceration*, Contusion#	Airbag & Belted	Impact direction
Seat back	20	2.3	Laceration*	Airbag & Unbelted	Other passengers
Airbag	19	2.2	Fracture**	Airbag & Belted	Occupant position (fore most)
Etc.	10	1.1	-	-	-
Total	865	100	-	-	-

* Laceration: 5.8% of thorax injuries
** Fracture: 14.7% of thorax injuries
# Contusion: 62.0% of thorax injuries

Figure 4. NASS/CDS case (2010-79-070) of thorax injury due to the belt web: belted passenger (rear most seat position) with airbag, Delta V 51 kph, Thorax AIS 6, ISS 75.

The major injury sources and associated injury patterns of abdomen are investigated (Table 4). Similar to thorax injury, the belt web was most frequent injury source (64%) followed by steering wheel (22%). For belt web, airbag was deployed for all AIS 3+ injuries (100%, 12 out of 12 cases) and the rear most seat position was also a dominant variable (64%, 7 out of 11 cases). In case of steering wheel, airbag and belted was the most common restraining condition for AIS 3+ injury level (52%, 12 out 23 cases) and the foremost seat position was a distinct variable (46%, 10 out of 22 cases). Other injury sources such as instrument panel, inner trim, airbag, and armrest showed relatively low occurrence frequencies. Figure 5 shows an example NASS/CDS case (2012-49-063) of abdomen injury due to the steering wheel.

Table 4. Injury pattern and source of abdomen.

Injury source	Injury frequency	Ratio (%)	Major lesion	Restraint	Injury variable
Belt web	252	63.6	Laceration*	Airbag & Belted	Occupant position (rear most)
Steering wheel	87	22.0	Laceration*, Contusion**	Airbag & Belted	Occupant position (fore most)
Instrument panel	15	3.8	-	-	-
Inner trim	10	2.5	-	-	-
Airbag	9	2.3	-	-	-
Armrest	9	2.3	-	-	-
Etc.	14	3.5	-	-	-
Total	396	100	-	-	-

* Laceration: 22.7% of abdomen injuries
** Contusion: 58.1% of abdomen injuries

Figure 5. NASS/CDS case (2012-49-063) of abdomen injury due to the steering wheel: belted driver (fore most) with airbag, Delta V 64 kph, Abdomen AIS 5, ISS 57.

The results of lower extremity are listed in Table 5. Instrument panel was most frequent injury source (50%) followed by floor (15%). In case of instrument panel, airbag and belted was the most common restraining condition for AIS 3 injury level (61%, 41 out 67 cases) and the reclined seat back was the main variable (75%, 50 out 67 cases). Lower extremity injury due to floor had airbag and belted condition (AIS 3 84%, 16 out of 19 cases) and fore most seat position (39%, 5 out 13 cases). The overweight of obese occupant was also a common variable at both instrument panel and floor. In case of foot controls, airbag and belted condition (AIS 3, 88%, 7 out of 8 cases) and rear most seat position (63%, 5 out 8 cases) are the most common restraint condition and the main variables. For belt web, airbag and belted condition (AIS 2, 100%, 4 out of 4 cases) and rear most seat position (67%, 2 out 3 cases) were obtained. Figure 6 shows an example NASS/CDS case (2012-09-012) of lower extremity injury due to instrument panel.

Table 5. Injury pattern and source of lower extremity.

Injury source	Injury frequency	Ratio (%)	Major lesion	Restraint	Injury variable
Instrument panel	789	49.5	Laceration*, Fracture**	Airbag & Belted	Occupant posture (reclined)
Floor	242	15.2	Fracture**	Airbag & Belted	Occupant position (fore most)
Foot controls	151	9.5	Fracture**	Airbag & Belted	Occupant position (rear most)
Belt web	148	9.3	Fracture**	Airbag & Belted	Occupant position (rear most)
Glove box door	95	6.0	-	-	-
Steering wheel	62	3.9	-	-	-
Etc.	108	6.8	-	-	-
Total	1595	100	-	-	-

* Laceration: 7.0% of lower extremity injuries

** Fracture: 26.3% of lower extremity injuries

Figure 6. NASS/CDS case (2012-09-012) of lower extremity injury due to the instrument panel: unbelted driver with airbag, Delta V 54 kph, Lower extremity AIS 3, ISS 34.

Numerical Simulation Model for Reconstruction of Injury Risk

Figure 7 shows the result of frontal sled impact simulation with various parameters in which the instantaneous motion at 80 milliseconds was selected for the comparison of dummy motion among simulation parameters, i.e., three restraining conditions, two seat positions, and three steering column tilt angles. The dummy kinematics and interactions with vehicle interior parts were interpreted by contact forces between body regions and airbag, steering wheel, and windshield and were summarized in Table 6. Since shoulder belt forces at all 18 cases were saturated to its limit force (about 5.0 kN) and thus it was not included at in the analysis.

- Head contact to steering wheel: Some cases (cases 2, 5, and 6) with belt+airbag condition at 68 and 79 kph impacts. With unbelted condition (cases 7-12) at all three impact speeds except case 11 (center position of seat and -3 degree of steering wheel tilt angle). With no airbag condition (cases 13-18), rear most seat position (Cases 14, 16, and 18) showed significant higher (89% at 56 kph, 20% at 68 kph, and 43% at 79 kph) contact forces between head and steering wheel than with center seat position (cases 13, 15, and 17) at all three impact speeds mainly due to the large excursion of the head.
- Head contact to windshield: No contact was observed with belted condition (cases 1-6, and 13-18). In all unbelted condition (cases 7-12) except case 9 (center position of seat and +3 degree of steering column tilt angle), contact forces between head and windshield were calculated.
- Chest contact to steering wheel: No contact was observed with belt+airbag condition (cases 1-6) at all three impact speeds. In unbelted with airbag condition (cases 7-12) at two higher impact speeds (i.e., 68 and 79 kph) except case 11 (center position of seat and -3 degree of steering wheel tilt angle), contact forces between chest and steering wheel were calculated. Belted with no airbag condition (cases 13-18) showed a mild contact between chest and steering wheel. Rear most seat position (cases 8, 10, 12, 14, 16, and 18) showed higher (48% at 56 kph, 27% at 68 kph, and 44% at 79 kph) contact forces between chest and steering wheel than center seat position (cases 7, 9, 11, 13, 15, and 17) at all three impact speeds.

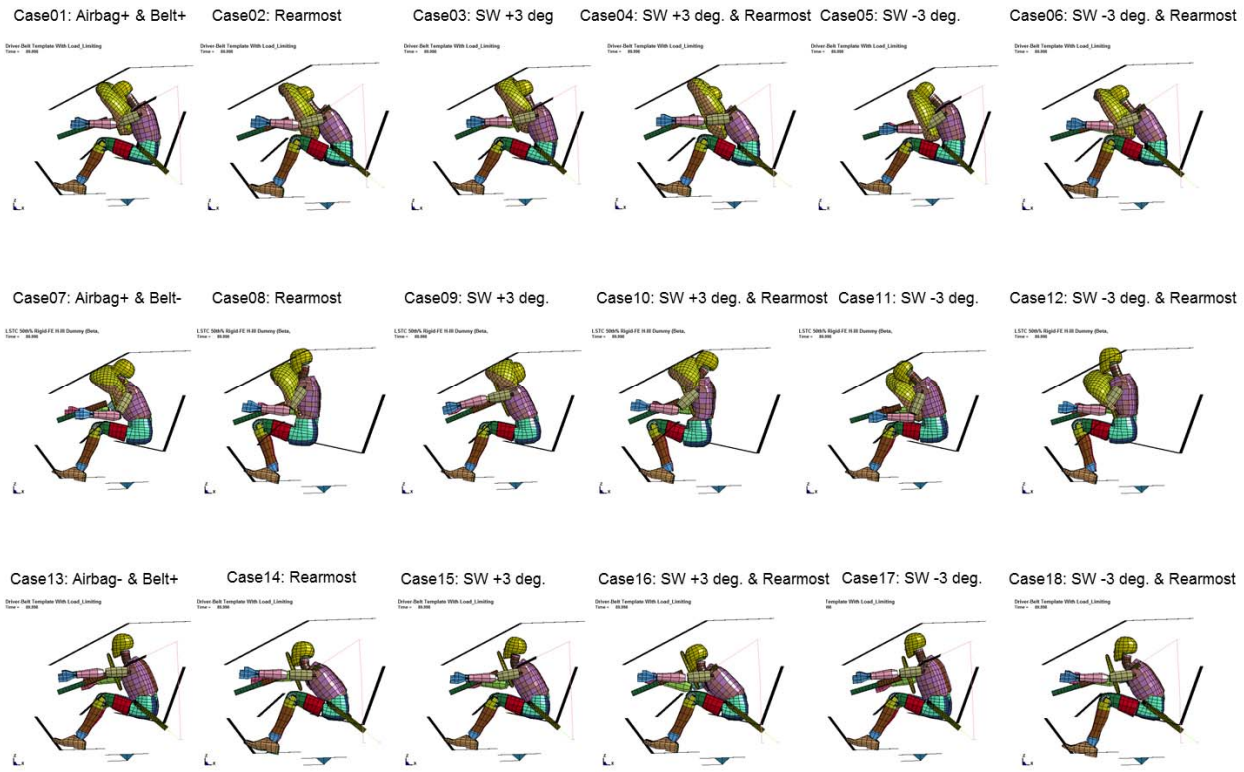


Figure 7. Simulation result with Hybrid III dummy model: 18 cases at 80msec with 56 kph impact speed.

Table 6. Result of frontal sled impact simulation with Hybrid III dummy.

Case No.	Air bag	Seat belt	Steering column Tilt angle (degree)	Seat position	Max. head contact force (kN)			Max. chest contact force (kN)		HIC	Max. chest deflection (mm)
					Airbag	Steering wheel	Wind shield	Airbag	Steering wheel		
56 kph impact											
1	+	+	0	Center	1.24	0	0	1.53	0	367	32.85
2	+	+	0	Rearmost	1.91	0	0	1.15	0	619	47.68
3	+	+	+3	Center	1.75	0	0	1.33	0	402	30.23
4	+	+	+3	Rearmost	2.08	0	0	1.08	0	639	46.36
5	+	+	-3	Center	1.10	0	0	1.48	0	367	35.55
6	+	+	-3	Rearmost	1.62	0.2	0	1.17	0	634	50.17
7	+	-	0	Center	1.26	0	7.02	2.14	0	776	10.90
8	+	-	0	Rearmost	1.21	0	8.13	3.16	0	1,365	14.81
9	+	-	+3	Center	8.3	0	0	6.06	1.69	2,044	13.41
10	+	-	+3	Rearmost	6.88	0	7.19	3.33	1.9	2,227	12.33
11	+	-	-3	Center	4.87	11.05	7.28	2.71	0	1,729	17.89
12	+	-	-3	Rearmost	0.78	0	8.94	2.49	0	1,227	15.35
13	-	+	0	Center	0	6.85	0	0	0	2,678	16.81
14	-	+	0	Rearmost	0	13.7	0	0	0	7,319	44.62
15	-	+	+3	Center	0	9.83	0	0	0	4,403	18.71
16	-	+	+3	Rearmost	0	20.39	0	0	0	10,790	45.27
17	-	+	-3	Center	0	8.25	0	0	0	2,982	18.70
18	-	+	-3	Rearmost	0	12.94	0	0	0	14,570	41.09
68 kph impact											
1	+	+	0	Center	1.51	0	0	1.58	0	648	36.35
2	+	+	0	Rearmost	4.14	1.70	0	1.29	0	1,625	56.74
3	+	+	+3	Center	1.78	0	0	1.72	0	522	33.29
4	+	+	+3	Rearmost	2.95	0	0	1.42	0	1,304	55.94
5	+	+	-3	Center	2.34	5.92	0	2.41	0	985	38.34
6	+	+	-3	Rearmost	7.97	6.79	0	1.27	0	2,856	54.49
7	+	-	0	Center	6.21	0	6.88	6.94	1.66	2,817	39.47
8	+	-	0	Rearmost	5.25	0	8.76	9.93	9.56	3,062	48.89
9	+	-	+3	Center	11.71	0	0	13.50	5.52	3,804	51.59
10	+	-	+3	Rearmost	7.00	0	7.59	7.81	6.14	3,761	77.47
11	+	-	-3	Center	5.46	10.67	7.92	3.58	0	2,732	14.97
12	+	-	-3	Rearmost	0.93	0	10.16	7.53	4.59	2,073	51.28
13	-	+	0	Center	0	13.45	0	0	0.59	10,160	20.81
14	-	+	0	Rearmost	0	19.43	0	0	0	20,260	46.91
15	-	+	+3	Center	0	16.74	0	0	3.74	9,164	22.34
16	-	+	+3	Rearmost	0	16.16	0	0	0	9,599	47.39
17	-	+	-3	Center	0	11.99	0	0	0	9,865	22.33
18	-	+	-3	Rearmost	0	14.78	0	0	0	24,740	42.60
79 kph impact											
1	+	+	0	Center	1.8	0	0	1.75	0	1,367	40.32
2	+	+	0	Rearmost	10.95	9.37	0	1.38	0	5,615	60.37
3	+	+	+3	Center	2.04	0	0	1.56	0	1,232	38.57
4	+	+	+3	Rearmost	12.94	0	0	2.18	0	4,109	59.43
5	+	+	-3	Center	2.09	8.07	0	1.94	0	1,573	44.05
6	+	+	-3	Rearmost	6.66	19.75	0	1.07	0	10,100	62.98
7	+	-	0	Center	6.4	0	7.58	6.2	3.19	2,812	50.18
8	+	-	0	Rearmost	5.33	0	9.27	8.06	24.2	4,275	77.08
9	+	-	+3	Center	8.13	0	2.46	12.48	10.01	3,489	75.03
10	+	-	+3	Rearmost	8.81	0	8.12	9.23	11.5	5,898	91.52
11	+	-	-3	Center	1.56	11.09	9.39	5.73	0	1,762	47.31
12	+	-	-3	Rearmost	1.07	0	10.18	11.66	21.09	2,935	81.76
13	-	+	0	Center	0	15.11	0	0	4.72	20,070	30.20
14	-	+	0	Rearmost	0	25.76	0	0	0	43,930	52.72
15	-	+	+3	Center	0	16.3	0	0	7.37	1,4170	43.83
16	-	+	+3	Rearmost	0	14.04	0	0	0.85	9,926	49.93
17	-	+	-3	Center	0	12.83	0	0	1.36	15,180	25.94
18	-	+	-3	Rearmost	0	23.22	0	0	0	37,370	43.55

The body regional injury risk was also assessed by two injury indices, i.e., HIC and chest deflection as follows:

Effect of restraining With belt+airbag condition (cases 1-6) at 56 kph impact, HIC values for all seat positions and steering column tilt angles were calculated under 1,000, the injury threshold in a compliance test and also showed a gradual increase with the impact speed. However, the belt only condition showed much higher HIC values at all three impact speeds than the other two restraining conditions mainly due to the head contact to steering wheel and windshield. This result shows the protection effect of airbag that becomes more significant at a higher impact speed. It is also noticeable that the increasing rate of chest deflection with airbag only condition is relatively much higher than the other two restraining conditions. In Figure 8and 9, mean values of HIC and chest deflection are respectively displayed with three restraining conditions and at three impact speeds. Each one represents average value with six variations (2 seat positions X 3 steering column tilt angles, Figure 9). Therefore the heights of error bar at mean value represent a degree of scattering (e.g., standard deviation) in six data points simulated with other two parameters, i.e., seat positions and steering column tilt angles.

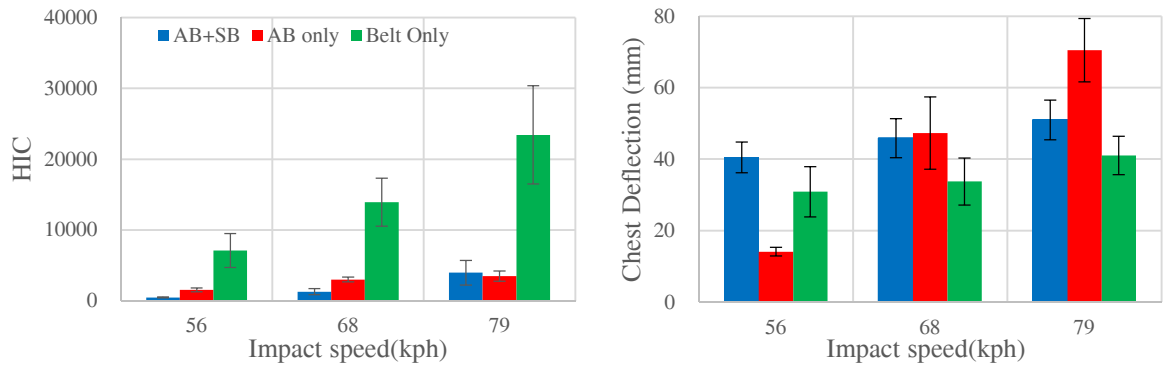


Figure 8. Head and thorax injury risks with restraining condition.

Effect of seat position Both HIC and chest deflection increased respectively by 100% and 60% at the rear most seat position compared to center position at all three impact speeds.

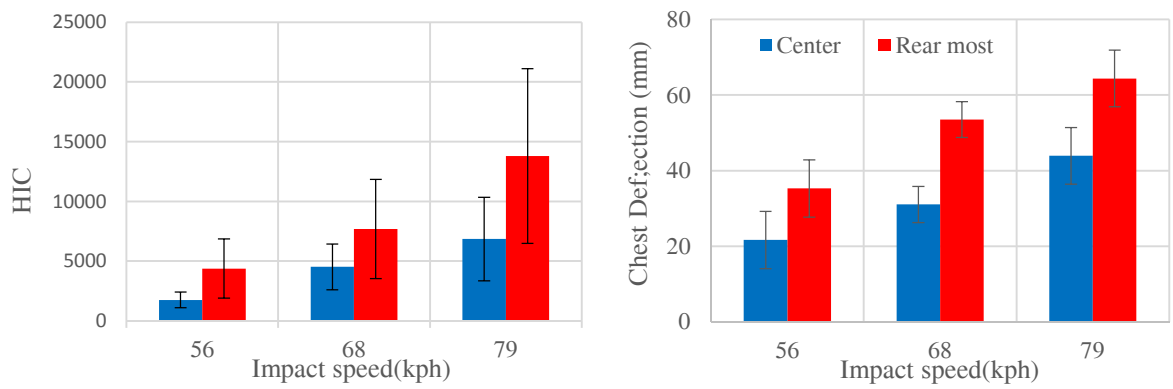


Figure 9. Head and thorax injury risks with seat position.

Effect of steering column tilt angle **The** HIC values showed quite different patterns at different impact speeds, i.e., respectively V shape, step up, and inverse V shape as a steering column is tilted in upper (+3 degree), middle(0 degree), or lower (3 degree, Figure 10). The chest deflections at 56 kph impact speed are in similar levels for all three tilt angles, while they became substantially higher with +3 degree case than two other tilt angles at 68 and 79 kph impact speeds.

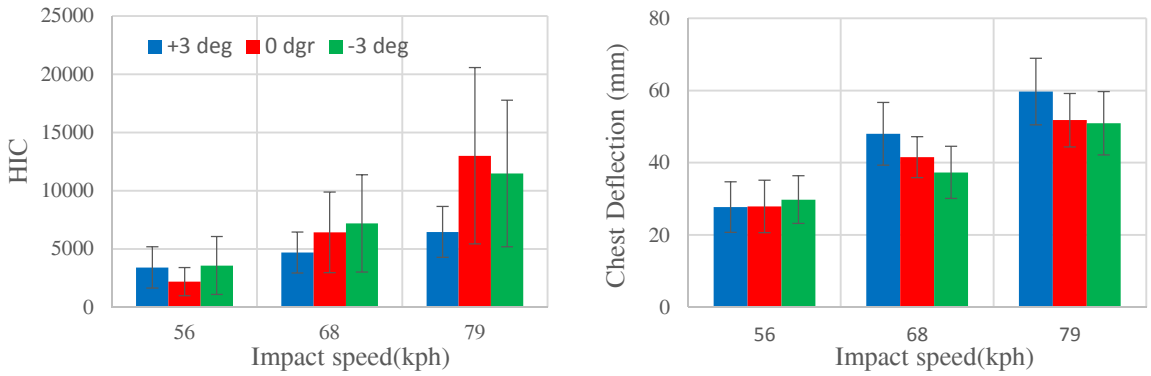
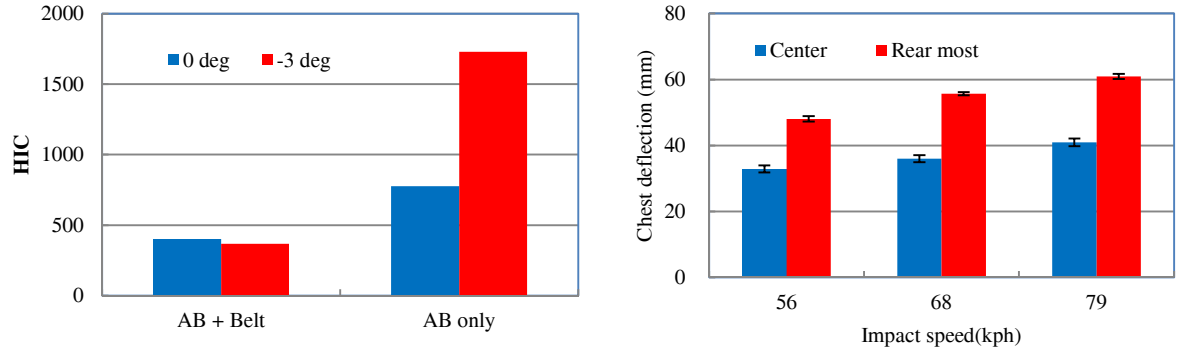


Figure 10. Head and thorax injury risks with steering column tilt angle.

<u>Correlation of injury risk between NASS/CDS data analysis and sled impact simulation</u> The windshield was the leading head injury source for unbelted driver with the full down steering column tilt position (Table 2). The predicted HIC values from sled impact simulation at 56 kph speed between center and full down steering column positions, i.e., cases 1 and 7 versus cases 5 and 11 showed much higher head injury risk at full down steering column position, especially with unbelted condition (Figure 11(a)). However this correlation becomes not so consistent at two other sled impact speeds.

The belt web was the most frequent injury source for thorax with airbag and rear most seat position (Table 3). The predicted chest deflection at all three sled speeds between center and rear most seat positions, i.e., cases 1, 3, and 5 versus cases 2, 4, and 6 shows much higher head injury risk at rear most seat position (Figure 11(b)).



(a) Head injury risk (b) Thorax injrury risk

Figure 11. Head and thorax injury risks for correlation with NASS/CDS analysis result.

Numerical Simulations using Human Body Model

Three configurations of the sled modeling in Figure 7, cases 1, 5, and 6 were selected for substituting the dummy model with the anatomically detailed human body model, i.e., GHBMC model (Figure 12). The comparison of thorax injury risk at a frontal impact between two drivers model were made at 68 kph impact speed. The thorax injury risks were assessed by number of rib fractures and chest deflection respectively from the GHBMC human body model and the Hybrid III dummy model. As listed in Table 7, the GHBMC model predicted 80% increase of thorax injury risk with the change of steering column tilt angle and seat position by 5 to 9 rib fractures while 40% increase of chest deflection by the Hybrid III dummy model.

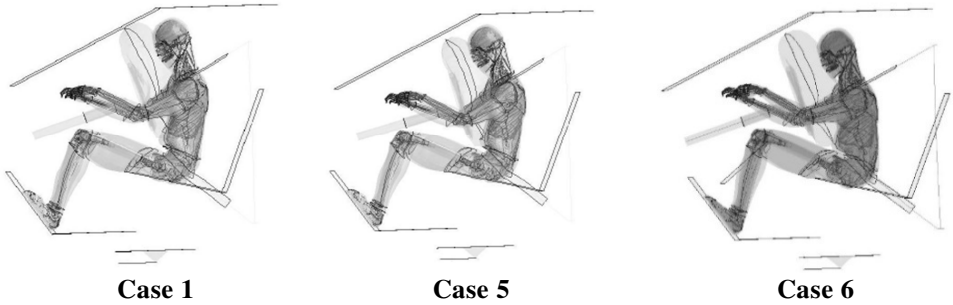


Figure 12. Front sled impact simulation with GHBMC human body model at 68 kph speed (Case 1: baseline model, Case 5: -3 steering column tilt, Case 6: -3 steering col1mn tilt + rear most seat position).

Table 7. Comparison of thorax injury risk between Hybrid III dummy and GHBMC human body model.

Steering column tilt	Seat position	GHBMC	Hybrid-III
		No. of rib fracture	Chest deflection (mm)
Mid	Center	5 (base)	36.35 (base)
Down	Center	6 (+20%)	38.34 (+6%)
Down	Rear most	9 (+80%)	54.49 (+40%)

CONCLUSIONS

The body regional injury risks of driver and front seat passenger at a frontal impact were investigated using 2009-2012 NASS/CDS data. Numerical sled impact simulations using two driver models, the Hybrid III dummy and the GHBMC human body model, were used to confirm the change of injury risk with restraining condition, steering column tilt angle, and seat position. Some of distinctive findings in this study are as follows:

- Windshield, side structure, and steering column equally contribute head injury risk as injury sources.
- Belt web is a dominant injury sources at thorax and abdomen injury risks.
- Instrument panel is main injury source at lower extremity injury risk.
- 80% of AIS 3+ head injuries by windshield as a injury source was found at the full down position of steering column tilt.
- 69% of AIS 3+ head injuries by steering wheel as a injury source was found at the full up position of steering column tilt.
- 65% of AIS 3+ head injuries by instrument panel as a injury source was found at the rear most seat position.
- 82% of AIS 3+ thorax injuries by belt web as a injury source was found at the rear most seat position.
- 64% of AIS 3+ abdomen injuries by belt web as a injury source was found at the rear most seat position.

- 75% of AIS 3 lower extremity injuries by instrument panel as a injury source was found at the reclined seat back.
- Both Hybrid III dummy and GHBMC human body model predict the increasing thorax injury risk at steering column down tilt angle and rear most seat positions. However, the GHBMC human body model was more sensitive, i.e., prediction of higher injury value than the Hybrid III dummy model.

In the future, the real world accident data analysis will be extended to side impact and the numerical sled simulation with GHBMC human body model for more biomechanical injury risk prediction, e.g., CSDM(Cumulative Strain Damage Measure) to predict DAI(Diffuse Axonal Injury) of head.

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