Investigation of Occupant Kinematics and Injury Risks in Semi-Autonomous Vehicle Collisions

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I. INTRODUCTION

Autonomous driving is one of the fastest developing vehicle technologies and is believed to be a possible driving scenario in the near future. Level 2 semi-autonomous driving is already common with Advanced Driver-Assistance Systems (ADAS), e.g. Lane Departure Warning System (LDWS), Forward Collision Warning (FCW) and Collision Avoidance System (CAS). Level 3 semi-autonomous driving will require the driver to intervene only if necessary, but the driver will not be required to monitor the vehicle's performance in the same way as for the previous levels. In semi-autonomous vehicles, the driver will be able to engage in other activities, such as entertainment, eating or resting. As a result, the driver's posture and the interior layouts will be more varied [1]. However, existing occupant restraint systems (airbags, seatbelts, etc.) are designed for normal occupant sitting postures, so they may not provide enough protection for the occupant in different postures (such as half-lying) during semi-autonomous driving [2-4].

The aim of this paper is to evaluate and compare the occupant kinematics and injury risks in different sitting postures in semi-autonomous vehicle collisions. The injury risks were evaluated by calculated dummy injury parameters.

II. METHODS

A simplified vehicle cabin model was developed and validated for this study. The cabin model consists of the body-in-white, instrument panel, steering wheel and collapsible steering column, carpet, seat, driver airbag, seatbelt, etc. The seat was modeled according to a physical seat in production. The seat rail and frames were modeled with elastic-plastic material and the seat cushion was modeled with low-density-foam material. Three seatback angles were used: 25°, 43° and 60°. The Thor dummy used has a high flexibility of pelvic angle adjustment. The dummy postures were adjusted to fit the seatback angles.

Hyperworks was used as the pre-post processor and LS-DYNA was used as the solver to perform the simulation. The dummy kinematics were investigated under two crash scenarios: a full front rigid barrier (FRB) crash at impact speed of 56 km/h, and collision against a mobile progressive deformable barrier (MPDB) at relative impact speed of 100 km/h.

III. INITIAL FINDINGS

Fig. 1 shows the kinematic responses of drivers in different sitting postures with the traditional restraint system in FRB scenario. It illustrates that as the driver leaning angle increases, the distance between head and the steering wheel increases, and thus the time to contact the airbag is delayed.

Submarining is the process where the lap belt slips off above the anterior superior iliac spine and results in abdomen and spine injuries. The submarining risk is associated with the leaning angle of the occupant upper torso. As shown in Fig. 2, when the seatback angle is set at 25°, the lap belt never slips off the iliac. When the seatback angle is set at 43° and 60°, the lap belt slips off the iliac at 100ms and 75ms respectively. These results show that when the seatback angle is set at 25°, there is no risk of submarining for the occupant. When the seatback angle is set at 60°, submarining occurs 25 ms earlier than when it is set at 43°. This could be an indication that as the leaning angle of the driver's upper torso increases, the submarining risk increases as well.

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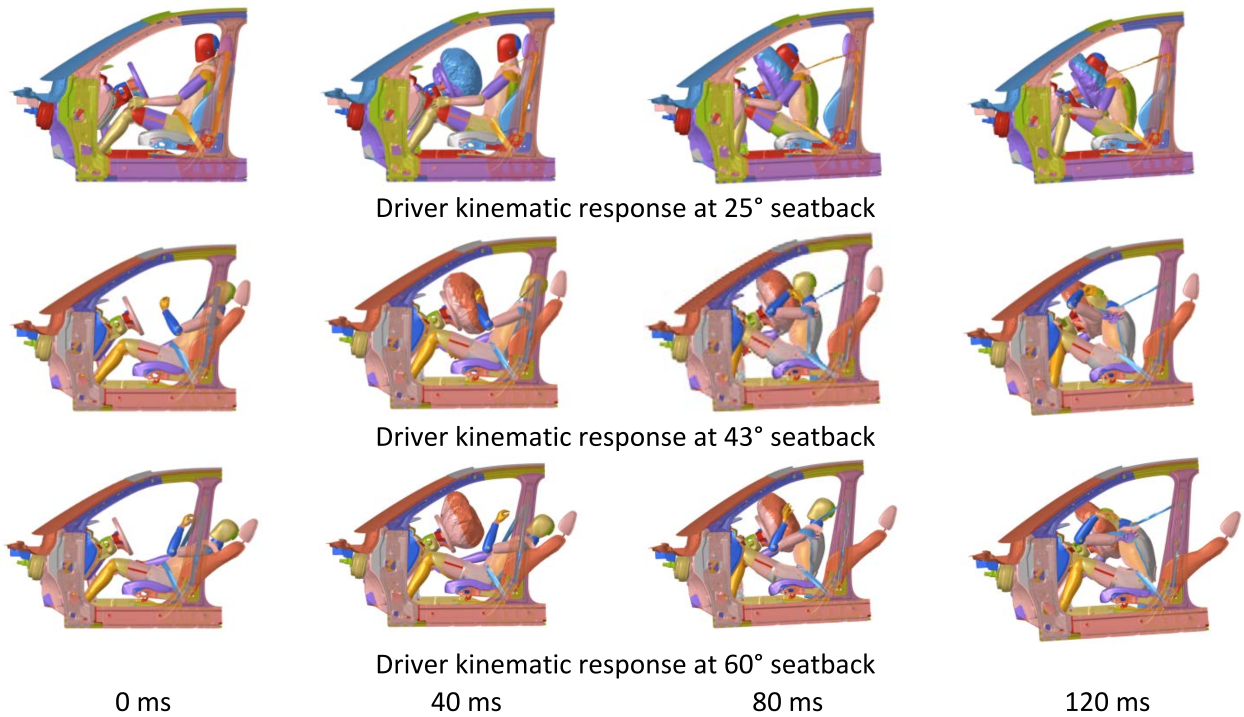


Fig. 1. Kinematics of drivers in different postures under FRB.

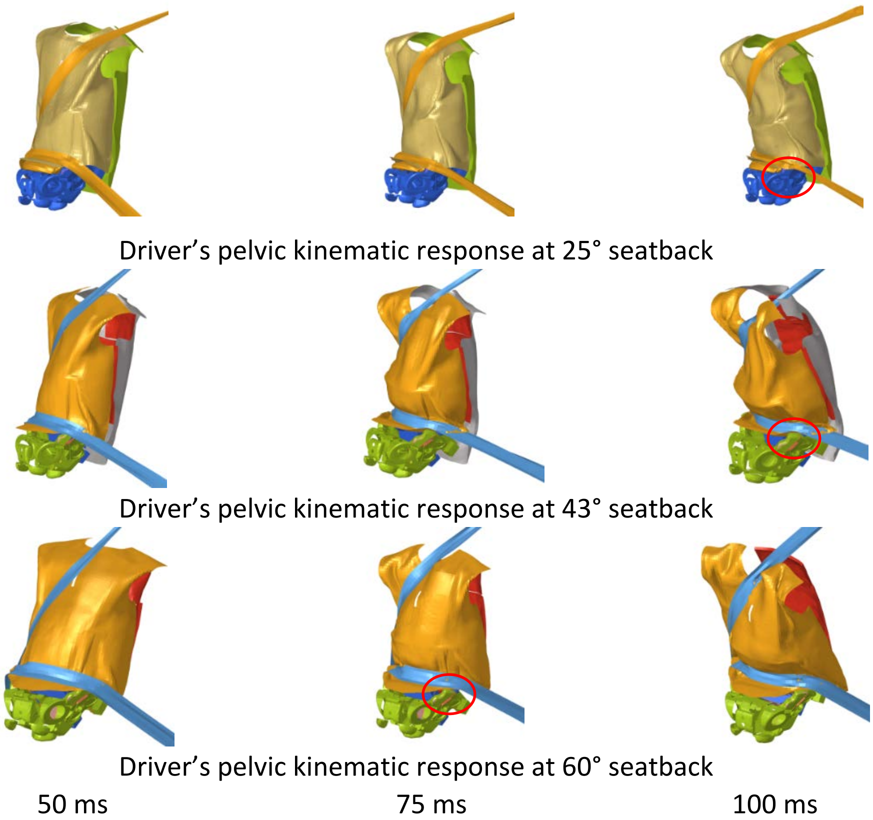


Fig. 2. Comparison of submarining responses of drivers in different postures under FRB.

Table I shows the comparison of injury parameters under FRB. The following four findings can be summarized.

(1) As the D-ring of the traditional seatbelt is on the B-pillar, the timing of the shoulder belt fully contacting the chest is delayed with the increasing of seatback angle. Then the head acceleration climbs sharply after the head is thrown forward with the restraint of upper torso. The HIC_{15} value reaches to 596 when the seatback angle is set at 43° or at 60°. HIC is based on translational accelerations, while BrIC is used for considering the brain injury resulting from head rotation. The values of BrIC increase from 0.66 to 1.16 and the BrIc value (1.16) of the driver at 60° seatback exceeds the US-NCAP limit of 1.05. Due to the increased head swing, the Nij values

increase as well.

(2) With the increase of the leaning angle, the restraint of the shoulder belt on the chest is weakened and the chest deflection is reduced.

(3) As occupant's abdomen engages with the lap belt due to submarining, the maximum abdominal compression increases from 60.5 mm to 82.4 mm.

(4) The injury values of femur and tibia show minor changes, and all are within reasonable ranges.

TABLE I

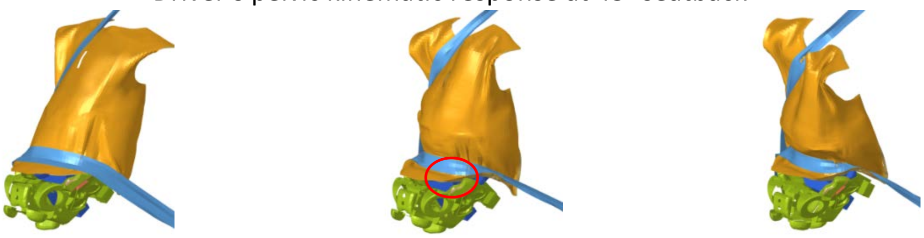
COMPARISON OF INJURY VALUES OF DRIVERS IN DIFFERENT POSTURES UNDER FRB

Backrest reclining angle	25°	43°	60°
HIC_{15}	223.2	596	596.3
Brain Injury Criterion(BrIC)	0.66	0.91	1.16
Neck injury criterion(N_{ij})	0.27	0.32	0.49
Maximum chest compression	51.7 mm	34.9 mm	35.8 mm
Abdominal compression	60.5 mm	80.6 mm	82.4 mm
Knee slide	7.6 mm	7.82 mm	6.3 mm
Femur compression	1.36 kN	2.18 kN	1.4 kN
Acetabulum compression	2.7 kN	1.5 kN	2.4 kN
Lower leg compression	1.98 kN	1.53 kN	1.67 kN
Upper tibia index	0.5	0.47	0.44

Fig.3 compares the interactions between the pelvis and the seatbelt with different driver sitting postures in MPDB crash scenarios. Similar to the simulation results of FRB, the submarining occurs at the leaning angles of 43° and 60°. A comparison of the injury values under MPDB shows that head, neck and abdominal injuries are more likely to be found with greater seatback angle.

Driver's pelvic kinematic response at 25° seatback

Driver's pelvic kinematic response at 43° seatback



Driver's pelvic kinematic response at 60° seatback

50 ms 75 ms 100 ms

Fig. 3. Comparison of submarining responses of drivers in different postures under MPDB.

TABLE II

COMPARISON OF INJURY VALUES OF DRIVERS IN DIFFERENT POSTURES UNDER MPDB

Backrest reclining angle	25°	43°	60°
HIC_{15}	246.5	529.2	157
Brain Injury Criterion(BrIC)	0.72	0.98	1.04
Neck injury criterion(N_{ij})	0.26	0.23	0.35
Maximum chest compression	50.7 mm	45 mm	38 mm
Abdominal compression	58.6 mm	79 mm	77 mm
Knee slide	7.9 mm	9 mm	6 mm
Femur compression	1.45 kN	2.2 kN	1.5 kN
Acetabulum compression	2.7 kN	1.7 kN	2.2 kN
Lower leg compression	2.55 kN	1.97 kN	2.63 kN
Upper tibia index	0.52	0.56	0.45

IV. DISCUSSION

In this study, the occupant kinematics and injuries in semi-autonomous driving vehicles were investigated in FRB and MPDB crash scenarios with different occupant sitting postures. When there is an increase of the driver's leaning angle, the risk of submarining is higher. The abdomen compressions due to submarining are increased, coming close to the tolerance limit of 88 mm proposed by Euro NCAP. The risk functions of AIS injuries are calculated by the following formulas as proposed in NHTSA's Request for Comments:

$$\mathrm{p}(AIS \geq 3) = \Phi\left[\frac{\ln(HIC_{15}) - 7.45231}{0.73998}\right] \qquad \mathrm{p}(AIS \geq 4) = 1 - e^{-\left(\frac{BrIC - 0.523}{0.647}\right)^{1.8}} \qquad \mathrm{p}(AIS \geq 3) = \frac{1}{1 + e^{(4.9372 - 4.5294Nij)}}$$

$$\mathrm{p}(AIS \geq 3) = 1 - e^{-\left(\frac{Rmax}{59.865}\right)^{2.7187}} \qquad \mathrm{p}(AIS \geq 3) = \frac{1}{1 + e^{(7.849 - 0.0886\delta_{max})}} \qquad (1)$$

TABLE III

COMPARISON OF INJURY RISKS OF DRIVERS IN DIFFERENT POSTURES UNDER FRB AND MPDB

	Injury Risk / Backrest angle	AIS 3+ Head P(HIC_{15})	AIS 4+ Brain P(BrIC)	AIS 3+ Neck P(Nij)	AIS 3+ Chest P(Chest Rmax)	AIS 3+ Abdomen P(Abdomen δ_{max})
FRB	25°	0.003	0.059	0.063	0.295	0.077
	43°	0.076	0.327	0.069	0.078	0.330
	60°	0.076	0.622	0.094	0.085	0.366
MPDB	25°	0.004	0.111	0.062	0.277	0.066
	43°	0.055	0.414	0.059	0.187	0.300
	60°	0.001	0.487	0.073	0.104	0.264

The injury risk probabilities for the head, neck and chest are shown in Table III. As the driver's leaning angle increases, the AIS 4+ brain injury risk increases significantly and may exceed 50%. The probability of AIS 3+ abdomen injury is approximately 30% when the backrest is set to 43° or 60°. However, the incidences of AIS 3+ head injury and neck injury are relatively low and the probabilities are less than 10%.

Therefore, when the driver chooses to lie down while the vehicle is driving autonomously, more attention should be paid to brain injuries and abdomen injuries under FRB and MPDB crash scenarios.

V. REFERENCES

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