

Can 1 –DOF Sled Tests Reproduce Real World Far-Side Crashes? A Finite Element Study

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Abstract A profound knowledge of the biomechanical responses of the occupants is elemental in the understanding and development of counter-measures for injury prevention and mitigation in far-side crashes. In far-side crashes, vehicles rotate in clock or counter-clockwise direction depending on the location of impact with respect to the center of gravity (CG) of the vehicle. Vehicle rotations can influence the kinematics of the occupants relative to the vehicle interior. Controlled laboratory tests are performed to mimic the biomechanical responses of the occupants in real world crashes. Frequently, these tests are performed using linear one degree of freedom (dof) sled systems utilizing standardized rigid seats without any rotational inputs. However, it is not yet understood if the 1 dof sled could reproduce occupant responses in real world far-side crashes. Therefore, the objective of the current study was to compare the occupant kinematics from simulated real world far-side crashes to the kinematics obtained from simulated sled tests, under similar loading conditions. The study was performed using validated whole vehicle model and whole-body finite element (FE) human body model (HBM) developed by the Global Human Body Models Consortium (GHBMC).

Keywords Far-side impacts, finite element modeling, human body.

I. INTRODUCTION

Each year, significant number of occupants are injured in far-side crashes [1-6]. In general, injury mechanisms in far-side impacts are thought to be significantly different from near-side impacts. Therefore, occupant protection strategies for far-side crashes must be different from near-side crashes. Previous studies based on National Automotive Sampling System/Crashworthiness Data System (NASS/CDS) data have indicated that the head is more likely to sustain severe injuries, followed by chest, and abdomen. In addition, these studies reported that the struck-side interior was the most frequent contacting structure associated with the vehicle occupant, followed by seat belt and passenger seat [1,3]. Fildes, Fitzharris [5] reported rib cage is the frequently injured anatomic structure in the chest, followed by lungs. Whereas, liver is injured frequently in the abdomen, followed by spleen. In a more recent study that was based on 111 Crash Injury Research and Engineering Network (CIREN) cases indicated that occupants sustain pelvic fractures in far-side crashes probably due to belt loading [6]. Another recent study performed whole vehicle FE simulations and reported the complex kinematics of the occupants when the vehicle was impacted at different locations [7].

Traditionally, controlled laboratory tests are used to delineate injury mechanisms to develop counter-measures. To date, however, there are few studies that have investigated biomechanical responses in far-side impact. Forman *et al* [8] tested three male PMHS under repeated lateral (90-deg) far-side impact on a sled with simplified boundary conditions. The study reported an interrelation between D-ring position, arm positions, pre-tensioning, and impact speed. Pintar, Yoganandan [9] tested six restrained PMHS under repeated lateral far-side impact on a sled using a buck with detailed boundary conditions. Shoulder retention effectiveness was analyzed using different belt configurations to reduce head excursion and injuries to the thorax. Frequently, these tests are performed using linear one degree of freedom (DOF) sled systems utilizing standardized rigid seats without any rotational inputs. However, it is not yet understood if the 1-DOF sled test could realistically reproduce occupant kinematics in real world far-side crashes.

To simulate side impacts with 1-DOF sled tests, the resultant of frontal and lateral velocities from real world accidents are used. The angle of resultant velocity is used to orient the rigid buck on the sled and magnitude of resultant velocity is used to accelerate the buck. The objective of the present study was to compare occupant kinematics from a sled test to kinematics from a real-world full vehicle crash.

1 DOF sled simulations were performed using resultant linear velocity of driver seat from full scale car simulation. To understand the effect of vehicle rotation, another set of simulations were performed using linear and rotational velocity of the driver seat from full vehicle simulation. The PDOF (principal direction of force) of changed by rotating the assembly from 0 to 80 degrees. Head, thorax and pelvis excursions from real-world full car simulations were compared to rigid buck simulation to understand the kinematics. The present study used a computationally efficient finite element human body model (FE-HBM) to perform whole vehicle and sled simulations. The full scale GHBM model was validated under far side in pure lateral and oblique orientations (Arun 2016 IRCOBI). The GHBM model used in this study is a simpler version of the full scale GHBM and is as biofidelic as the full-scale model. However, the simplified GHBM was validated under pure lateral condition using PMHS experiments as in our previous study (Arun 2016 IRCOBI).

II. METHODS

The objective of this study was achieved through four tasks: 1. Clockwise (CW) and counterclockwise (CCW) far-side cases were queried using CIREN database focusing on AIS2+ injuries to the head, thorax, and pelvis. The corresponding CDC codes were used to identify six initial impact conditions 2. A whole vehicle FE model was validated under side impact condition using data from IIHS database 3. Whole vehicle FE simulations were performed using GHBM HBM and occupant kinematics were extracted 4. Same HBM was used to perform simulations of a sled FE model with varying orientations. Two sets of simulations were performed - one with linear pulse and the other with linear and rotational pulses. The FE-HBM trajectories were extracted from all the simulations and compared with the whole vehicle simulation trajectories.

CIREN data analysis

The CIREN database was used to query far-side cases with AIS2+ injuries to the occupant. The query resulted in 122 cases in which one occupant was seated opposite to the side of the vehicle the force vector was applied to at impact. They were divided into two groups based on the rotation of the vehicle - clockwise and counterclockwise. This resulted in a total of six groups, that is, injuries to head, thorax, and pelvis for the two rotational directions. The evidence for occupants' injuries was reviewed using pattern of injury diagrammed on body and anatomical mannequins. The patterns were grouped based on injuries to the head, thorax, and pelvis. The CDC injury codes were identified for all the cases under each of the six groups. For each group, statistical distribution was performed using each column of the six-digit code. The most frequent columns were identified and assembled to represent a nominal impact condition for the group. For example, the first two columns of the CDC code indicates the principal direction of force (PDOF). Statistical distribution was performed on these columns to identify the most frequent PDOF. The process was repeated for each column of the CDC code to obtain six nominal initial impact conditions for the six groups. The initial velocities in the x- and y-directions were calculated by averaging the velocities of the cases under each group. To represent a nominal vehicle fleet, a passenger sedan vehicle was used in the present study. In order to represent a realistic stiffness of modern vehicles, a 2010 Toyota Yaris vehicle model was used in the present study. This model was developed by the National Crash Analysis Center (NCAC) consortium.

FE-HBM and Vehicle Validation

The experiments used to validate the GHBM model were previously conducted by Pintar et al. (2007). The detailed description of the finite element buck model is available in our previous study (Arun 2016 IRCOBI). The buck system included a seat pan, seatback, b pillar, 3-point belt system, horizontal center console, and vertical lateral load plates designed to engage specific anatomical regions. The 3-point belt system included a standard low-elongation lap and shoulder belts that are anchored at standard locations. The entire buck model was given an initial velocity of 8.3 m/s using *INITIAL_VELOCITY keyword. The deceleration pulse from the experiments were directly applied to the seat using the *BOUNDARY_PRESCRIBED_MOTION LSDYNA keyword. The displacements of the head CG, T1, T12, and sacrum with respect to the seat were compared with PMHS excursions. Correlation and analyses (CORA) was used to quantify the goodness-of-fit between simulation and experimental responses such as head, T1 vertebrae and T12 vertebrae resultant accelerations.

The whole vehicle model was validated in the side impact mode using test data archived by Institute for Insurance Highway Safety (IIHS). The regular norm to perform side impacts tests is impacting the vehicle with a

movable deformable barrier (MDB). Full-scale simulations were performed using restrained GHBM model seated on a sedan model using a movable deformable object (MDB) under far-side lateral impact condition (Figure 1). A 2010 Toyota Yaris was selected from the National Crash Analysis Center (NCAC) consortium for the current study. The vehicle model was validated in the frontal impact model and was not validated in the side impact. However, the default OEM seat position of this model was full-forward. In all the simulations, to simulate a nominal seating position, the fore-aft position of the driver and passenger seats were adjusted to their mid-positions. The GHBM model was translated and rotated, and placed just above the OEM seat. The HBM was then settled on the OEM seat using acceleration due to gravity. The same simulation was also used to gravity settle the whole-vehicle model on the rigid floor that was constructed using shell elements. A three-point seatbelt system was used to restrain the GHBM model. The system also included a pretensioner (100 mm pull-in at 10 ms) and retractor with a 4 kN load-limiter. The pretensioner was triggered using the crash pulse to encumber the GHBM model, whereas, the load limiter maintained a constant load of 4 kN on the shoulder belt to simulate a realistic loading condition. The airbags were refrained in the vehicle to get maximum occupant excursions. The whole vehicle model was struck by a 1500 kg MDB at 50.2 km/h. Per IIHS side impact crash test protocol, the left edge of the MDB was aligned 62.6 cm behind the vehicle's front axle in the pre-impact test configuration. To simulate the impact between the vehicle and the MDB, all the nodes of the MDB model were assigned an initial velocity and allowed to impact the vehicle. In order to validate the side stiffness of the whole vehicle model, the post-crash vehicle crush profile was extracted by measuring nodal displacements at the mid-door horizontal level of the vehicle. The extracted crush profile of the model was compared with the experimental crush profile of a 2007 Toyota Yaris obtained from the IIHS experimental database. Although 2010 model year of the vehicle was used in simulations, 2007 model year was the closest available data in the IIHS data archive. The HBM was placed inside the vehicle to simulate a realistic inertial distribution and no data were extracted from the HBM.



Figure 1. Yaris validation setup using IIHS test.

Whole vehicle simulation

Following the validation of the vehicle model, the initial impact conditions and velocities obtained from the statistical analyses of the CIREN cases were used to perform whole vehicle simulations. The restrained HBM was positioned inside the validated vehicle model as discussed in the previous section. Arun, Umale [7] reported that narrow objects result in severe injuries compared to wide objects. Therefore, to simulate worst-case scenarios, a 10-inch diameter rigid pole was used in all the simulation in the present study. In all the six cases, the rigid pole was placed in the corresponding positions obtained from the CIREN analysis. To simulate the principal direction of force (PDOF) of the impacts, initial velocities were applied to the vehicle model in the x- and y-directions, obtained from CIREN analysis (Figure 2).

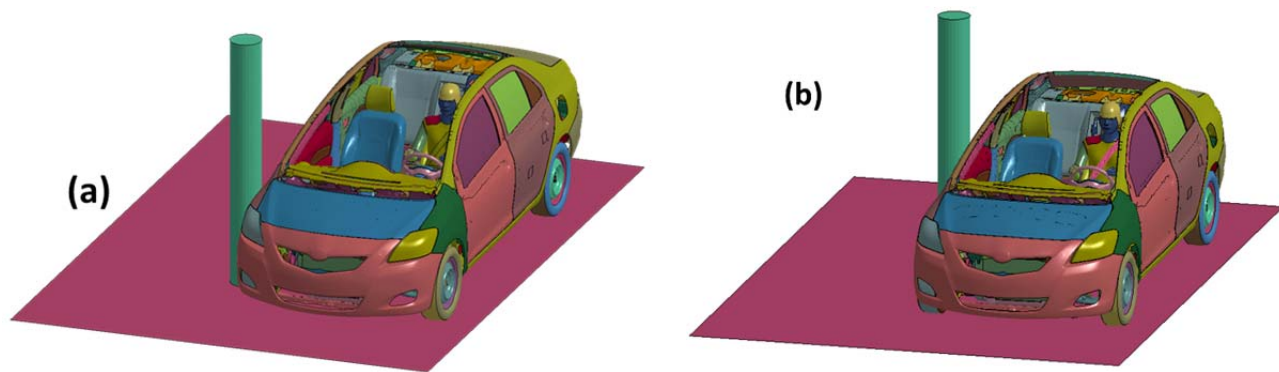


Figure 2. Setup of CIREN case showing (a) A pillar impact and (b) B-pillar impact.

The HBM excursions were extracted at the head, T12, and pelvis in the traverse plane (x-y plane). Because the vehicle was expected to rotate in clockwise and counter-clockwise directions after impact, measuring the excursions in the global co-ordinate system would not have resulted in realistic data. Therefore, a local reference axis was defined that was attached to the vehicle on driver side roof rails, where the deformation was negligible. This axis translated and rotated along with the vehicle and the excursions were measured with respect to this local coordinate system. The excursion data were collected using the SAE sign convention. Resultant linear velocity(m/s) and rotational velocity(rad/sec) about z axis were measured from the driver seat CG. The peak rotational velocity measured to be about 4rad/sec. The velocities were used as input to the rigid buck simulations.

Sled simulations

The rigid buck assembly is traditionally used to study occupant kinematics in automotive crashes. The buck experiments are used for reproducibility and the assemblies are reusable thus economically beneficial. Moreover, buck assemblies are considered to yield relatively comparable results. Thus, a detailed finite element model of a sled buck was constructed using various element types, and appropriate materials (Figure 3). The sled platform and components were not explicitly modeled in the simulation, however, the constraints associated with the sled system were mathematically implemented using constraints. The rigid seat was constructed using shell elements and assigned steel material property that was used during contact and mass approximations. The backrest of the seat was constructed using rigid shell elements, and attached to the seat frame using tied constraints. Rigid shell elements were used to construct a B-pillar that was used to anchor the seatbelt. A generic low-elongation three-point seatbelt system was used to restrain the GHBM model. One end of the seatbelt was attached to the B-pillar and the other end was attached to the right-hand side of the occupant at the pelvis level. In all the simulations, the occupant was assumed to be the driver. The shoulder belt anchor point was approximately 90 mm above and 120 mm behind the midpoint of the shoulder and in line with the end of the shoulder. The seatbelt system was made using shell and one-dimensional elements. The belt region that interacted with the GHBM model was created using shell elements, whereas the other regions were modeled using one dimensional elements. D-rings were modeled in appropriate places as observed in real world seatbelt system. Rigid plates were included in the setup to simulate a realistic boundary condition. Surface-to-surface contact interaction definitions were assigned between load plates and the HBM.

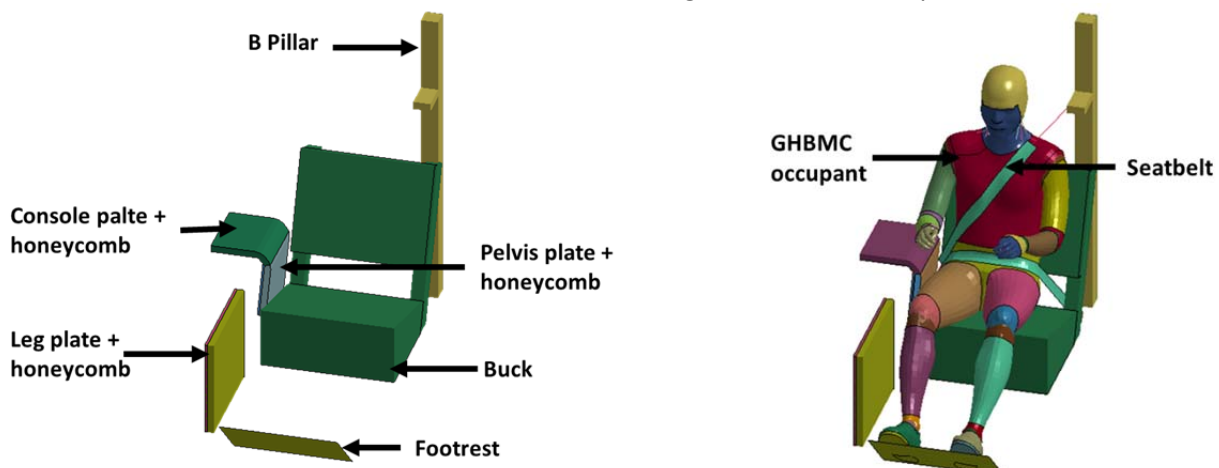
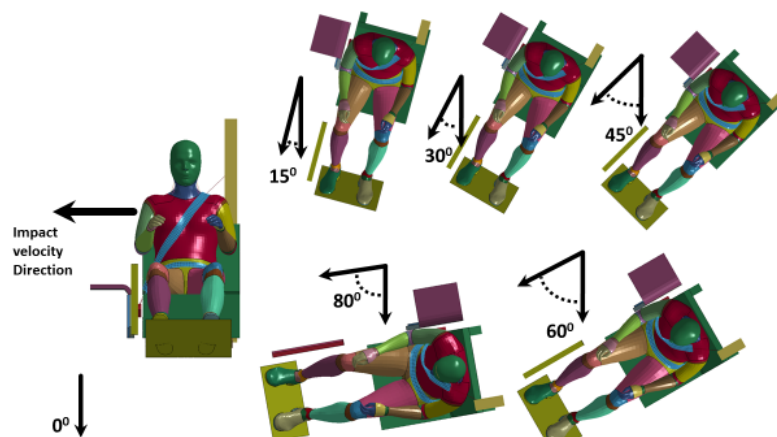


Figure 3. FE setup of the sled buck.

Each of the six whole vehicle cases were simulated using different buck orientations, namely - 0 (pure lateral), 15, 30, 45, 60, and 80 degrees (Figure 4). In order to compare the influence of rotational input, two sets of such simulations were performed. One set of simulations we performed using linear resultant velocity pulse obtained from the center of gravity (CG) of the whole vehicle simulations. Another set of simulations were performed using a combination of linear and rotational velocity pulses obtained from the whole vehicle simulations. In other words, a single and double degree of freedom sled systems were simulated in the present study. This simulation matrix resulted in a total of 72 sled simulations for CW and CCW group. The excursions of the HBM at head, T6, and sacrum were extracted with respect to the rigid seat. These excursions were compared with the excursions obtained from the whole vehicle simulations.

**Figure 4. Buck orientations**

III. RESULTS

CIREN data analysis

The initial impact conditions and velocities for the six scenarios are given in Table 1. The velocities ranged from 7.6 to 12.9 m/s. The head cases in both the impact directions resulted in higher y-direction impact velocities compared to other cases. For brevity, a brief description of the CDC codes are presented here. The first two columns represent the principal direction of force (PDOF). The second column represent the side of impact (R:right). The third column represent the horizontal location of impact. The fourth column represent the extent of vertical impact (A: all). The fifth column represent the size of the impacting object. The last column represent the extent of intrusion – larger number represent higher intrusion level.

Table 1. Initial Impact conditions and average velocities from CDC data analysis.

Orientation	Injured Body Region	CDC Code	Impact Position	X vel m/s	Y vel m/s
CCW	Head	02RYAW4	A Pillar	2.54	10.30
	Thorax	02RYAW3	A Pillar	4.40	9.07
	Pelvis	02RYAW3	A Pillar	3.69	7.56
CW	Head	02RPAW3	B Pillar	3.79	12.86
	Thorax	02RPAW3	B Pillar	3.70	10.94
	Pelvis	02RPAW4	B Pillar	3.61	10.97

FE-HBM and Vehicle Validation

The GHBM head, T1, and T12 displacement with respect to seat from the validation simulation are compared in Figure 5. The head lateral excursion was on higher side, whereas the T1, T12 and sacrum displacements were comparable to the experiments. Head, T1 and T12 vertebrae accelerations are compared to the PMHS data in Figure 6, Figure 7 and Figure 8 respectively. The GHBM accelerations were comparable to experimental PMHS data. The combined CORA rating for head, T1 vertebrae and T12 vertebrae accelerations was 0.86, 0.66 and 0.6 respectively. The average combined CORA ratings for all the accelerations was 0.7.

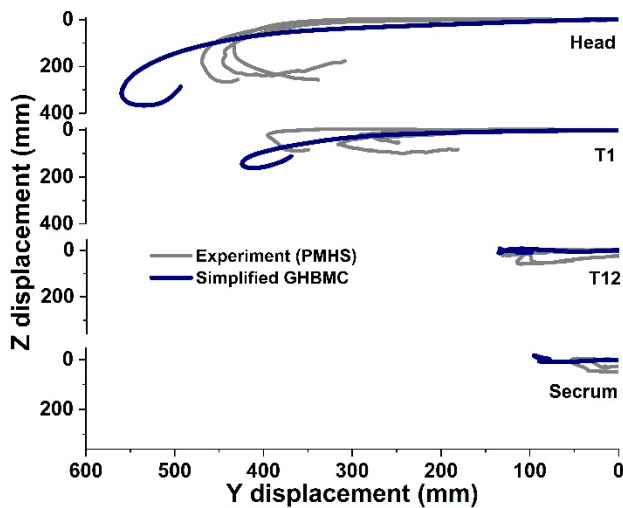


Figure 5. Regional displacements in lateral impact

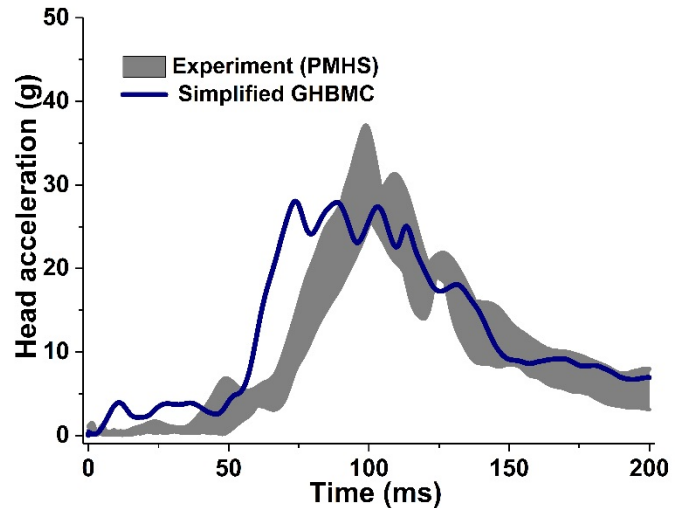


Figure 6. Head acceleration in the lateral impacts

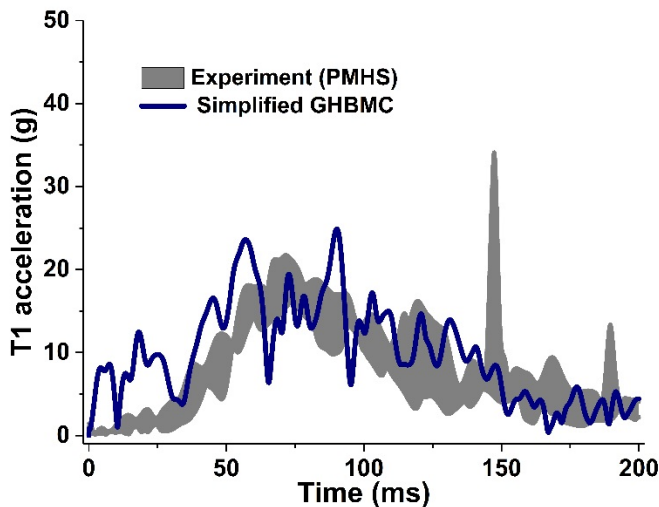


Figure 7. Head acceleration in the lateral impacts

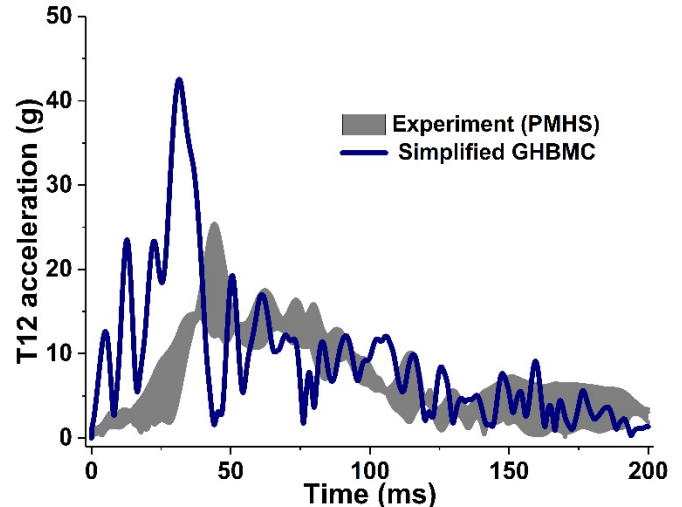


Figure 8. Head acceleration in the lateral impacts

The simulation took 21 hours to complete on a high-performance cluster. During the early phase into the impact, both the deformable region of the MDB and the vehicle deformed until temporal equilibrium was attained between the two structures. At approximately 160 ms into the event, the vehicle was accelerated away from the MDB due to the momentum transfer between the two structures. Visually, the deformations on the FE and the physical vehicles showed acceptable correlation. The deformations were visibly high in the vicinity of the B-pillar and the deformation gradient decreased in the vicinity of A- and C-pillars. Severe plastic deformations in the vicinity of B-pillar was observed in both the FE and physical vehicle. However, the visual comparison showed higher deformations in the vicinity of the rear and front tires in the model compared to the physical vehicle. The quantification of these deformations is shown in Figure 9. The intrusion was compared at the mid door position (Figure 10), where it was maximum. Overall, the model marginally over-predicted the deformation in the A-, B-, and C-pillar regions. This difference in prediction was higher at the A- and C- pillar compared to the B-pillar. The intrusions at the A- pillar in the FE and physical vehicles were 12 and 0 cm, respectively, whereas, the intrusions at the B- and C-pillars were 25 and 27 cm and 2 and 10 cm, respectively (Figure 10).

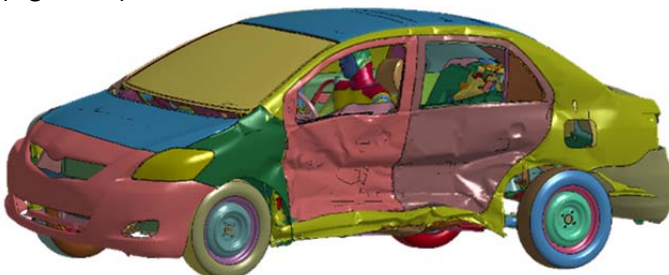


Figure 9. Plastic deformation in FE and physical vehicle.

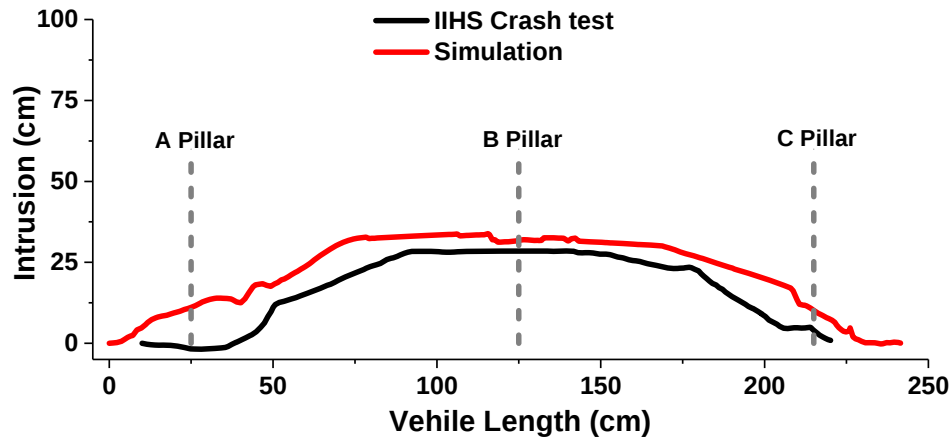


Figure 10. Comparison of intrusion at FE and physical vehicle.

Whole vehicle simulations

Based on the CIREN analysis, the rigid pole was positioned at the A-pillar region for the three cases in the counter-clockwise direction, whereas, the pole was positioned at the B-pillar for the clockwise impacts. Each simulation took approximately 5 hours to solve on a high-performance computational cluster. In all the six cases, immediately after the vehicle contacted the rigid pole, the vehicle structures near the contact point deformed locally. However, as more vehicle structures engaged the intruding pole, the local deformation reduced resulting in gross rotation of the vehicle. Although, the local deformation followed by gross rotation was a common sequence of events in all the cases, the rotational velocity of the vehicle with respect to the z-axis varied depending on the location of the contact point with respect to the CG of the vehicle. The CG of the FE model was centrally located below the console between A and B pillar. It was 74cm away from A pillar, 45cm away from B pillar and 32 cm above the ground. In addition, the rotational speed varied with the initial impact velocities. Based on these two criteria, the rotational speed was higher in the CW impacts compared to the CCW impacts, and head cases resulted in higher gross rotations compared to the other two cases.

In all the cases, the HBM moved to the lateral direction relative to the vehicle coordinate system, at approximately 15 ms into the event. In the CCW cases, upon impact the vehicle decelerated while the HBM traveled towards the impact point (A-pillar) with its initial velocity. The HBM, however, was eventually restrained by the seatbelt. Upon the seatbelt engagement, the HBM changed direction and traversed towards the passenger side of the vehicle (Figure 11(b)). Similar phenomenon was observed in all the CCW cases, however, the head case resulted in higher lateral excursion compared to the other two cases. In the CW impacts, the HBM accelerated towards the impact point (B-pillar). This phenomenon can be seen in Figure 11(a). However, the direction of the lateral excursion progressively changed from pelvis to head. In this case, due to the HBM's acceleration towards the B-pillar and its interaction with the seatback, the HBM kinematics resulted in counter-clockwise rotation about its own z-axis. Among the three CW cases, head resulted in the highest lateral excursion. In the CCW cases, the peak lateral excursions for the head, thorax and pelvis injury cases were 479, 379 and 370 mm, respectively. In the CW cases, the peak lateral excursions were 429, 341 and 317 mm, respectively.

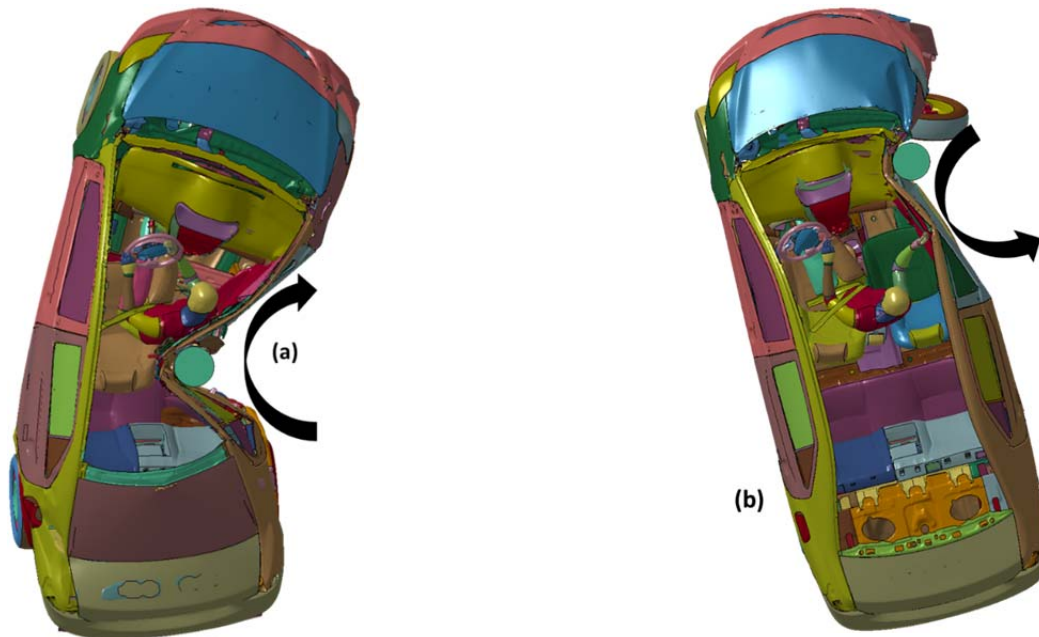


Figure 11. (a) B pillar impact showing occupant hitting B pillar, (b) A pillar impact showing occupant swinging towards passenger seat.

Sled simulations

Each of the 72 simulations took approximately 1 hour to solve on a high performance cluster. In all the cases, as the buck orientation changed from pure lateral (0 degree) towards frontal (80 degree), the lateral excursions decreased and forward excursion increased. In all cases, none of simulations resulted in accurate prediction of the excursions observed in whole vehicle simulations. However, 45 deg cases were the nominal buck orientation to closely approximate whole vehicle excursions. The final excursion coordinates for head, t6 and sacrum in the x-y plane is presented for all the cases in Table 2,

Table 3, Table 4 and are plotting in Figure 14, Figure 15, Figure 16, Figure 17, Figure 18 and Figure 19.

Table 2. Final excursion coordinates for head.

Cases	Car		0 deg		15 deg		30 deg		45 deg		60 deg		80 deg	
	Y disp	X disp	Y disp	X disp	Y disp	X disp	Y disp	X disp	Y disp	X disp	Y disp	X disp	Y disp	X disp
1-DOF														
Head(CW)	429	197	643	0	705	101	604	269	458	394	325	493	155	566
Pelvis(CW)	318	168	485	16	530	82	471	208	360	297	253	370	110	426
Thx(CW)	342	173	468	15	516	76	495	215	340	265	230	334	97	401
Head(CCW)	479	34	701	42	759	88	662	277	495	419	339	516	188	578
Pelvis(CCW)	371	196	513	28	581	61	508	150	355	263	232	333	95	385
Thx(CCW)		302	513	-20	575	73	500	192	371	301	257	377	111	433
2-DOF														
Head(CW)	429	197	743	196	690	317	541	431	386	490	221	533	33	527
Pelvis(CW)	318	168	575	130	550	227	438	318	331	374	191	410	34	410
Thx(CW)	342	173	609	142	586	240	464	335	348	393	199	433	38	433
Head(CCW)	479	34	408	-55	511	0	450	98	418	190	255	275	173	390
Pelvis(CCW)	371	196	397	-22	474	37	443	82	334	168	213	257	109	335
Thx(CCW)	379	302	397	-27	462	27	434	104	344	200	242	291	134	371

Table 3. Final excursion coordinates for T6.

	Car		0 deg		15 deg		30 deg		45 deg		60 deg		80 deg	
Cases	Y disp	X disp	Y disp	X disp	Y disp	X disp	Y disp	X disp	Y disp	X disp	Y disp	X disp	Y disp	X disp
1-DOF														
Head(CW)	307	-23	449	25	494	50	447	144	336	228	221	298	87	342
Pelvis(CW)	251	-19	356	18	402	29	360	102	272	165	174	217	59	253
Thx(CW)	266	-29	337	17	383	29	351	80	256	140	159	189	51	233
Head(CCW)	301	14	442	34	483	50	468	137	351	220	222	292	102	323
Pelvis(CCW)	251	55	340	27	378	32	364	61	260	124	153	171	43	198
Thx(CCW)	243	114	359	22	404	30	376	87	275	160	173	213	56	246
2-DOF														
Head(CW)	307	-23	515	107	514	179	419	253	280	292	157	317	17	309
Pelvis(CW)	251	-19	428	75	436	119	346	180	244	217	142	239	21	238
Thx(CW)	266	-29	443	80	454	126	363	189	253	228	147	251	21	250
Head(CCW)	301	14	259	12	338	16	325	24	279	84	164	149	90	218
Pelvis(CCW)	251	55	249	11	310	21	308	21	234	66	142	126	49	168
Thx(CCW)	243	114	258	13	323	12	314	28	244	92	158	158	66	208

Table 4. Final excursion coordinates for Sacrum.

	Car		0 deg		15 deg		30 deg		45 deg		60 deg		80 deg	
Cases	Y disp	X disp	Y disp	X disp	Y disp	X disp	Y disp	X disp	Y disp	X disp	Y disp	X disp	Y disp	X disp
1-DOF														
Head(CW)	168	-130	198	0	209	7	237	27	217	46	138	61	30	64
Pelvis(CW)	145	-94	173	16	186	24	218	-28	183	0	104	23	20	39
Thx(CW)	149	-115	161	-15	172	-23	199	-26	173	1	95	24	20	42
Head(CCW)	180	39	182	-30	182	-31	218	-36	201	-28	130	-26	12	0
Pelvis(CCW)	139	48	130	-18	128	-19	166	-26	177	-25	98	-7	18	9
Thx(CCW)	151	83	153	-16	162	-24	201	-31	183	-13	106	11	19	28
2-DOF														
Head(CW)	168	-130	226	-37	264	-26	249	3	181	19	111	29	-1	45
Pelvis(CW)	145	-94	195	-28	223	-26	218	0	144	16	90	24	6	38
Thx(CW)	149	-115	197	-29	226	-28	226	-1	153	15	97	23	6	38
Head(CCW)	180	39	127	14	130	18	130	-14	150	-16	130	15	35	29
Pelvis(CCW)	139	48	115	-14	110	-21	142	-14	154	-4	101	12	18	11
Thx(CCW)	151	83	126	-12	128	-16	167	-17	163	-1	104	21	21	23

Representative (0 deg) cases of occupant kinematics for CW and CCW impacts are shown in Figure 12 and Figure 13. In the CCW loading, for the head case, the 1-DOF sled system over predicted the head and T6 excursion magnitudes observed in the whole vehicle simulation (Figure 17), whereas the sacrum excursion showed better prediction. In both the 1- and 2-DOF simulations, the seatbelt slipped from the HBM resulting in poor retention for the 0, 15, and 30 deg cases. But the seatbelt retention was better for the 45, 60, and 80 deg cases. However, excursion estimation was better in the 2-DOF sled simulations compared to 1-DOF sled simulations. The trajectories of the 2-DOF were curved as observed in the whole vehicle simulation, whereas, the trajectories were predominantly linear in the 1-DOF simulations. For the thorax and pelvis cases, the 0, 15, and 30 deg 1-DOF simulations over predicted the excursions due to poor seatbelt retention at the head and T6 regions, whereas, the prediction was better in the 45 deg cases due to better seatbelt retention. For the 2-DOF simulations, the 0, 15, and 30 deg cases over predicted the lateral excursions, whereas, 60 and 80 deg cases under-predicted the lateral excursions. In the CCW impacts, the lateral head excursions were over-predicted in

both the 1- and 2-DOF simulations in the 0, 15, and 30 deg cases and under-predicted in the 60 and 80 deg cases. However, the 45 deg cases in both the impact rotational directions closely approximated the lateral excursions. None of the simulations predicted the T6 and pelvis, whereas, the 45 deg simulations closely approximated the lateral excursions.

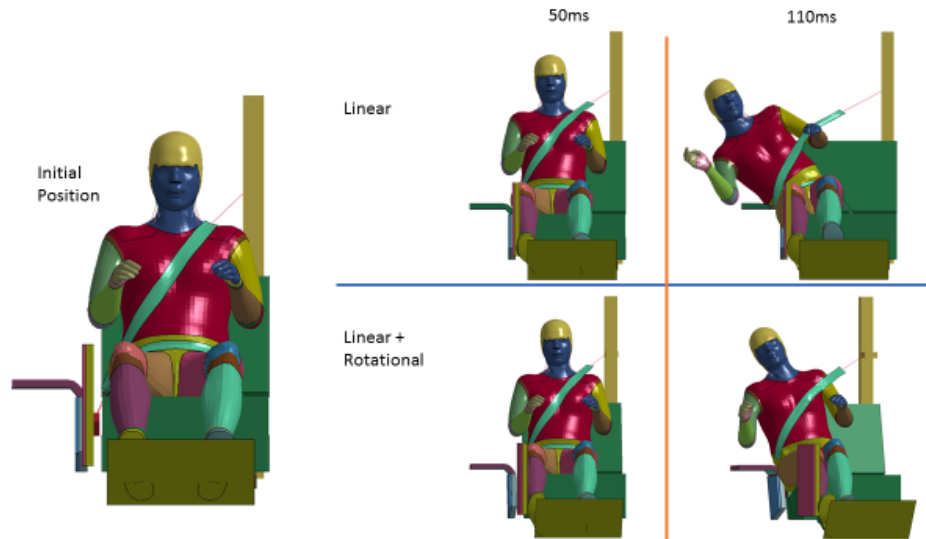


Figure 12 Counter clockwise impact (0 deg)

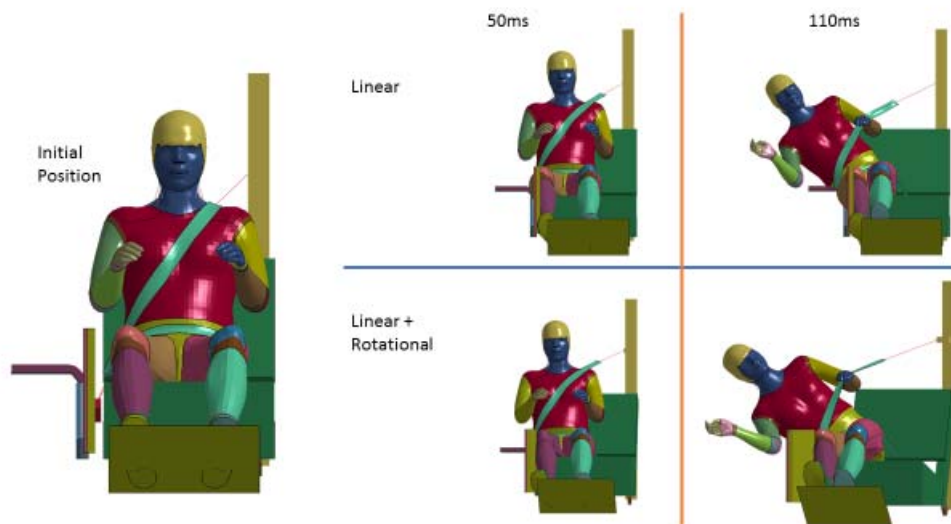


Figure 13 Clockwise impact (0 deg)

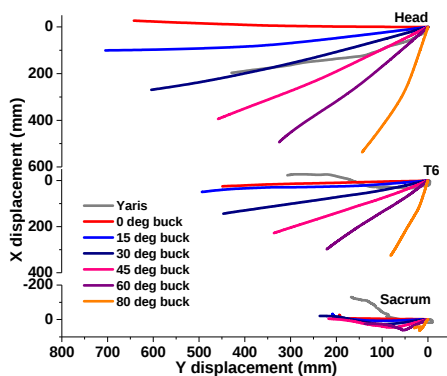


Figure 14. (a) CW head case with linear velocity as input.

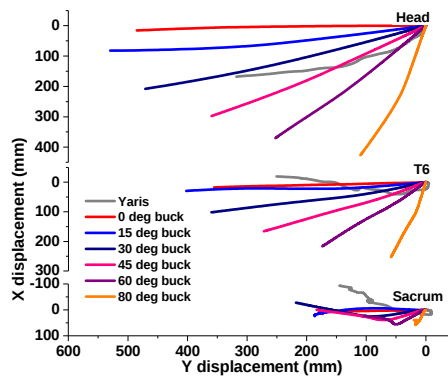


Figure 15. (a) CW pelvis case with linear velocity as input.

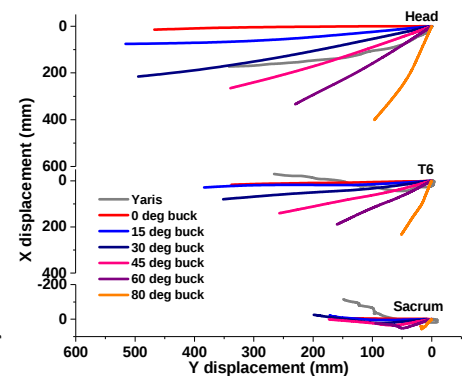


Figure 16. (a) CW head case with linear velocity as input.

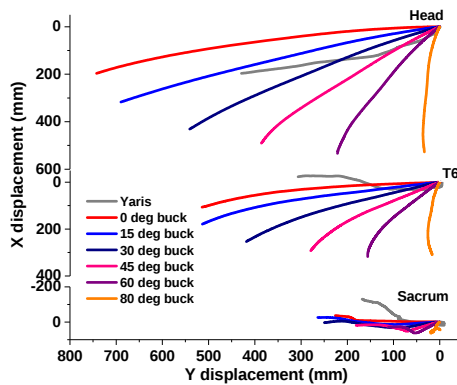


Figure 14. (a) CW head case with linear + rotational velocity as input.

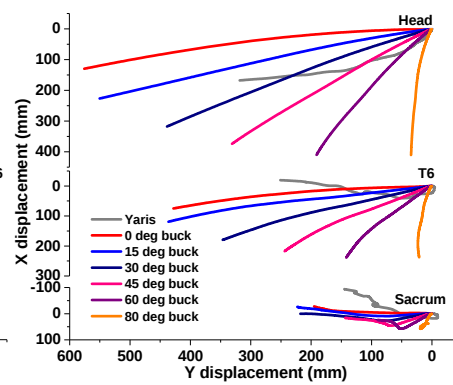


Figure 15. (a) CW pelvis case with linear + rotational velocity as input.

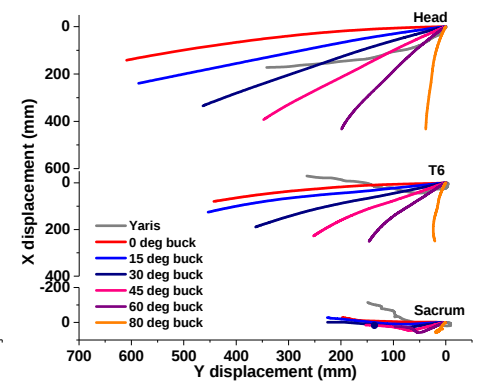


Figure 16. (a) CW head case with linear + rotational velocity as input.

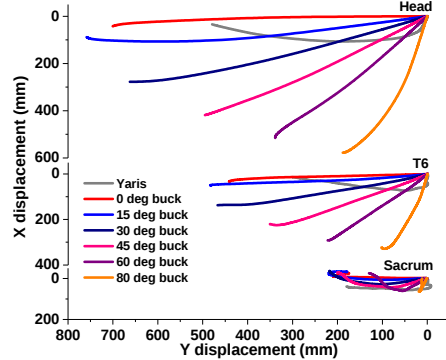


Figure 17. (a) CCW head case with linear velocity as input.

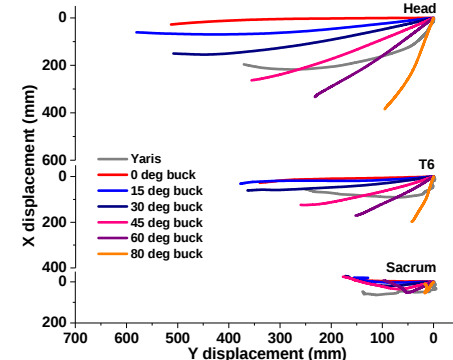


Figure 18. (a) CCW pelvis case with linear velocity as input.

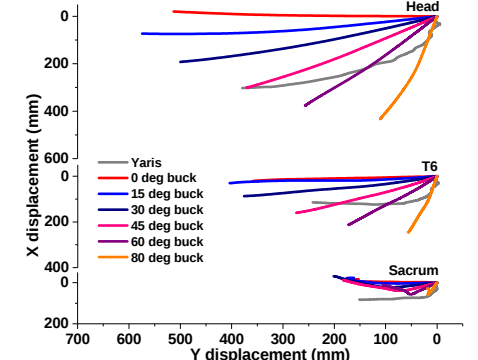


Figure 19. (a) CCW thorax case with linear velocity as input.

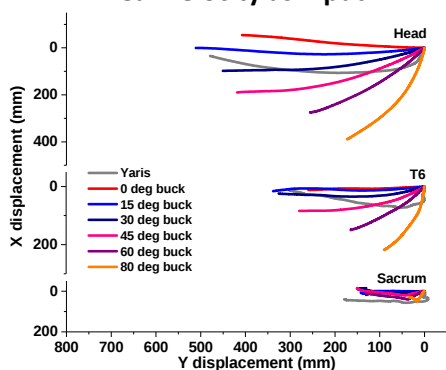


Figure 17. (b) CCW head case with linear + rotational velocity as input.

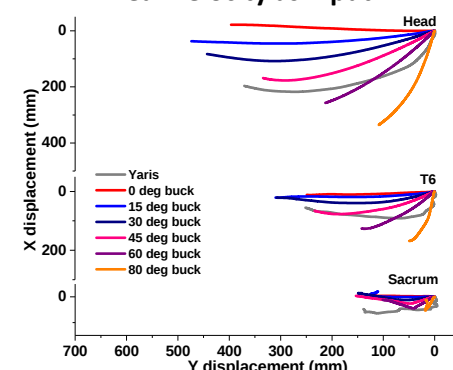


Figure 18. (b) CCW pelvis case with linear + rotational velocity as input.

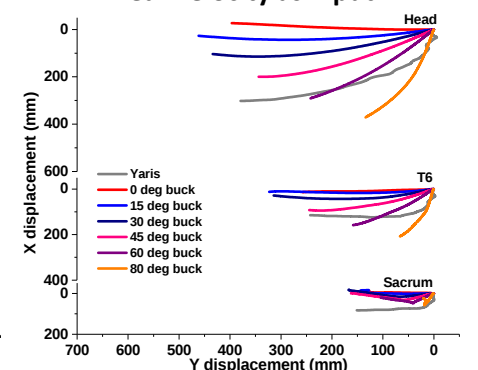


Figure 19. (b) CCW thorax case with linear + rotational velocity as input.

IV. DISCUSSION

CIREN data analysis

As indicated in the introductory texts, the objective of the present study was to compare occupant kinematics obtained from a linear 1-DOF and linear plus rotational 2-DOF sled systems to the occupant kinematics obtained from whole vehicle far-side crash. The present study used a validated computationally efficient finite element human body model (FE-HBM) to perform whole vehicle and sled simulations. The objective was achieved by querying CW and CCW far-side cases using CIREN database focusing on AIS2+ injuries to the head, thorax, and pelvis. The corresponding CDC codes were used to identify six initial impact conditions. The initial conditions were used on a whole vehicle model. To ensure a realistic response, the whole vehicle FE model was validated under side impact condition using data from IIHS database. Following the validation, whole vehicle FE simulations were performed using GHBM HBM and the occupant kinematics were extracted. Same HBM was used to perform simulations of a sled FE model with varying orientations. Two sets of simulations were performed - one with linear pulse and the other with linear plus rotational pulses. The FE-HBM trajectories were extracted from all the simulations and compared with the whole vehicle simulation trajectories. The CIREN data showed the highest velocities for the head cases in both the CW and CCW impacts. Arun, Humm [7] have shown

that direct impact of the occupant head with the intruding structures in the passenger side is the primary source for head injuries. The impact velocity should be high enough to significantly intrude the occupant compartment for the occupant to reach the passenger side intruding structures. This phenomenon accords with the high velocities obtained from the CIREN cases for the head impact cases.

FE-HBM validation

The whole vehicle model used in the present study marginally over predicted the deformation observed in the physical test. In other words, the FE model structures (cross members, sill, door members) that engaged the MDB were grossly less stiffer compared to the physical vehicle. Although this variation was higher in the A-pillar region compared to the B-pillar region. During the A-pillar impact in the present study (CW impact), this reduced stiffness at the A-pillar region is likely to increase the local deformation. This increase in the local deformation in the vicinity of the A-pillar region may reduce the gross rotational velocity of the vehicle upon impact. Although uncertainty exists in approximating the difference in the velocities between the stiffer and less stiffer A-pillar structures. In addition, the validation simulation was performed on the driver side to match the experimental data, whereas, the whole vehicle simulations in the present study were performed on the passenger side. Symmetrical stiffness was assumed due to the lack of experimental validation data.

Whole vehicle simulations

The location of the impact point with respect to the CG of the vehicle influenced the gross rotational direction of the vehicle. However, impact along the line of the CG of the vehicle is likely to result predominantly in gross translation of the vehicle in the direction of the impact vector. The HBM traversed towards the point of impact in all the cases. In other words, upon impact, in the CW impacts in which the pole was placed at the B-pillar, the HBM traversed towards the B-pillar. Similarly, the HBM traversed towards the A-pillar in the CCW impacts. Because of this phenomenon and presence of lap belt, the T6 and pelvis excursions were predominantly in the lateral direction in the CW cases, whereas, the A-pillar excursion had components in both lateral and frontal directions. Contrary to expectations, the HBMs rotated about their own axes in the opposite direction of the vehicle rotation. That is, in the CCW impacts the vehicle rotated in the CCW direction, however, the HBM rotated in the CW direction (Figure 11). Similarly, in the CW impacts, the vehicle grossly rotated in the CW direction, however, the HBM tend to rotate in the CCW direction about its z-axis. Taken together, these results suggest a complex interaction between the impact location and vehicle CG, impact location and HBM GC, and HBM interaction with the lap and shoulder belts. This requires further investigation to delineate these complex interactions.

Sled simulations

Occupant excursions in farside crashes are more complex compared to the frontal and near-side impacts. The kinematics of the occupants are likely to depend on the impact location, impact objects, impact velocity, and the interaction between the seatbelt and the occupant [7]. It may be arduous to incorporate all these variable while trying to reproduce real world kinematics using a sled system. In other words, certain compromises have to be made to closely reproduce the real world kinematics on a sled system. In addition, adding a rotational DOF to the sled system improved the trajectories and magnitudes of the excursions in the CCW impacts, whereas, no improvement in prediction was observed in the CW impacts. This is because in CCW impacts the occupant retention was improved as the shoulder belt was accelerating “against” the occupant’s thorax, whereas, in CW impacts the occupant retention was poor as the seatbelt was moving “away” from the occupant’s thorax. The next best option available is to predict the maximum excursions depending on the application under considerations. For example, to simulate a head injury case in a B-pillar impact, approximating lateral excursions may be more important than frontal excursion, whereas, in a A-pillar impact approximating a combination of lateral and frontal might be important.

Figure 20 present the maximum excursions in the lateral and frontal directions for the 1-DOF and 2-DOF sleds. These data were compared with the maximum excursions obtained from the whole vehicle simulations. In all the simulations, the 45 deg cases predicted the head, T6, and sacrum excursions in the lateral direction with the 1-DOF sled system. The green vertical line represents the 45 deg case, and the intersection of this line with the horizontal dotted line and the excursion lines (red and blue) indicate a good match. However, for the maximum frontal excursion did not show a clear pattern.

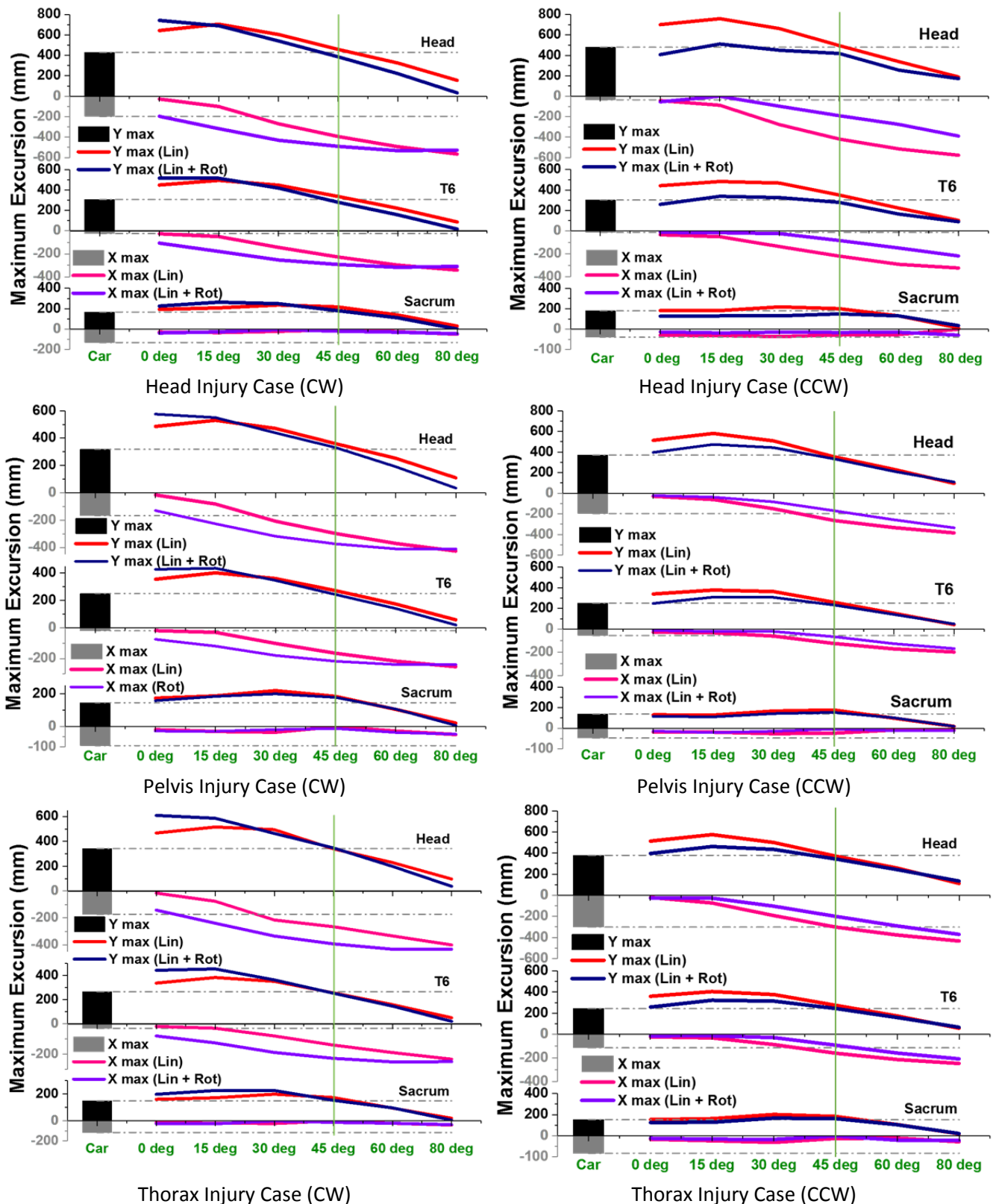


Figure 20. Comparison of Maximum head, t6 sacrum excursion in x and y directions for all 6 groups.

The study shows that rotation plays a key role in occupant kinematics in vehicle crash and 45deg PDOF closely reproduces the occupant kinematics under far side. However, the study has few limitations. As per the available data, the validation of the full vehicle was performed using a movable deformable barrier which results in distributed loading on the vehicle, whereas to exercise the accidents scenarios pole impacts were used, which results in concentrated loading on the vehicle. To have a closer response under pole impact the vehicle must be validated under pole impact. Though factors such as seat validation under far side and GHBM seat and seatback interactions may not influence the results much, it worth mentioning that the study lacks these aspects of the study. The simplified GHBM model was validated only under lateral impact with a CORA coefficient of 0.7 for head, T1 and T12 vertebrae accelerations. Further validation of GHBM in oblique scenario is required. Another limitation of the study is the simplification of rigid buck setup. The vehicle components

dashboard, passenger seat, central console, etc. were not modeled explicitly.

V. CONCLUSIONS

The validation of the whole vehicle model showed acceptable correlation with the experimental data. In general, occupant kinematics from all the simulations using the linear 1-DOF buck resulted in low correlations in all the simulations. The 2-DOF, however, showed higher correlation compared to the 1 dof buck simulations for the CCW impacts. But showed poor correlations with the CW impacts. Because of the complex kinematics observed in the whole vehicle far-side crashes, accurate reproduction of these kinematics may not be possible with both 1- and 2-DOF sled systems. In all the simulations, the 45 deg cases correlated well with the head, T6, and sacrum excursions in the lateral direction with the 1-DOF sled system. However, the maximum frontal excursion did not show a clear pattern.

VI. ACKNOWLEDGEMENT

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