Injuries, mechanisms, kinematics, and loading of head-neck-torso in small overlap frontal impacts

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Abstract Frontal crashes can be classified as full, offset, or small overlap impacts. While the former two impacts have received considerable attention in crashworthiness and promulgation of world-wide standards, small overlap crashes have undergone limited analyses from field and laboratory investigation perspectives. The objective of the present study was to analyze small overlap impacts using data from the Crash Injury Research and Engineering Network database and determine the head-neck-torso kinetics from full-scale vehicle tests. Head-neck kinematics and loads, and chest deflections from four cruxes were obtained from the Test Device for Human Occupant Restraint (THOR – NT version without modifications), positioned in the driver seat. Head contact occurred with the forward and outboard interior components of the vehicle; traditional crash metrics are inadequate descriptors; and less than full structural engagement contributes to increased vehicle deformations, enhanced occupant motions, and injury susceptibility. The mechanism of head and torso injuries was hypothesized to be due to the asymmetric loading and kinematics of the thorax and head-neck complex, resulting in sagittal and coronal motions with less than optimal interaction with the frontal airbag. Acknowledging that these impacts have not been systematically analyzed for injuries, mechanisms, occupant kinematics, and dummy measures such as multi-point sensing and head-neck trajectories and loads, the present study sheds light in these areas.

Keywords Chest injuries, head injuries, frontal impact, biomechanics, real-world data, occupant kinematics

I. INTRODUCTION

Field data and laboratory-driven tests have been used in frontal, rear and side impacts, and rollovers, to investigate occupant safety in motor vehicle environments [1]. Focusing on frontal crashes, collisions can be classified as full, offset, or small overlap impacts [2]. While the former two types of collisions have received considerable attention in crashworthiness and promulgation of world-wide standards for occupant safety, small overlap impacts have undergone very limited analyses from real world and laboratory investigation perspectives. Limited structural engagement in these crashes may expose occupants to differing kinematics, especially the head-neck complex and torso regions of the human body [3]. Recent studies have shown that small overlap impacts are susceptible to more trauma than full or offset impacts [4, 5]. Consequently, the objective of this study was to (a) analyze field data and injuries, and (b) conduct full-scale vehicle crash tests to determine the head-neck complex and thoracic kinetics.

II. METHODS

(a) **Field data and injury analysis:** Data were extracted from the Crash Injury Research and Engineering Network (CIREN) database with the following inclusion-exclusion criteria: direct-impact damage should not extend inboard of longitudinal vehicle structure. Criteria used for determining the engagement was based on the width of direct-damage, collision deformation codes, location of the center of direct-damage relative to the vehicle line and crush profiles. The selection criteria included non-ejected belted and unbelted adult drivers (greater than 16 years of age), and rollovers were excluded. Only passenger vehicles were considered. Status was obtained of frontal and side impact airbags. According to the CIREN criteria, all occupants were admitted to Level One Trauma Centers. Fatalities were also included in the ensemble. The following variables were extracted: size and nature of the collision partner to examine the potential influence of stationary object or vehicle-size match; extent zone and crush distances; occupant demographics; Abbreviated Injury and Injury Severity Scores; and association of injuries to other body regions in occupants sustaining head-neck-thoracic

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trauma. Medical records such as trauma bay records, x-rays, computed tomography scans, operative room records, nurses and progress notes; and vehicle inspection, exemplar vehicle, and on-scene photographs were also a part of the analysis. Body mass index (BMI) was calculated by dividing the total body mass by the square of the stature.

(b) **Full-scale vehicle tests:** Vehicle-to-pole tests were conducted to determine the kinematics and loading of the in small overlap impacts. They were chosen to determine the effects of a newer versus older structural member design, and small versus full-size vehicles. The matrix included the following tests: one with 2010 model year, small car (wheelbase 2550 mm); one with 2007 model year, full-size car; and one each with 2005 and 2009 model years, small car, and the structural member designed to distribute the load due to small overlap impact was different between the 2005 and 2009 cars. Three-point belted, mid-size Test device for Human Occupant Restraint (THOR) was positioned in the driver seat, following protocols including NCAP procedures. The vehicle under test was positioned on a "flying floor," supported by wheels located approximately 10 cm from the track. Each vehicle was placed in the neutral or second gear, and parking brakes were engaged. The vehicle was initially rotated counterclockwise on the floor such that the midsagittal plane of the dummy head was aligned with the central axis of the pole. The flying floor along with the vehicle under test was accelerated to the preset target speed of 15.6 m/s such that only the vehicle impacted the 25 cm diameter stationary pole, simulating a small overlap impact. The distance between the pole and the starting accelerating location of the floor-vehicle setup was approximately 125 m. The floor was released before vehicle impact with the pole. While the vehicle continued to impact the pole at a constant velocity, the floor was stopped by contacts on its leading end with heavy duty energy absorbers. The impact of the vehicle with the pole induced counter clockwise rotation, as viewed from the top, prior to rest. The entire event of the impact with the pole and rotation of the vehicle occurred on the flying floor.

Twelve cameras at 1000 f/s were used: four were onboard, two on the sides, one on the roof, and one underneath the foot of the dummy; eight off board cameras, one positioned mid-laterally on the driver side, one focusing on the steering column, and one left overall; an overhead overall and a close up view of the windshield; a front left overhead oblique view focusing on the chest and head; a front overhead oblique view of the windshield; and a front overall oblique view to capture the overhead kinematics. A handheld camera was used to capture the real time event at 30 frames per second. Targets were placed on the dummy: one each at the center of gravity of the head and tip of the nose; one 125 mm below the chin on the chest centerline; and one representing the inion location on the THOR. Colored chalk on the face and head were used to determine contact regions. The seat was fully down in the center for-aft position for positioning the dummy. The shoulder belt was placed at its highest position and pulled taught on the dummy according to the New Car Assessment Program (NCAP tests). The Lap belt was pulled taught and D-ring was placed in its highest position.

Instrumentation consisted of 180 channels. Briefly, linear accelerometers were used for head accelerations including a nine accelerometer package inside the dummy head. Load cells were used to record upper and lower neck forces and moments. Four crux potentiometers inside the chest were used to compute the thoracic deflections at multiple locations. Uniaxial accelerometers were used at T1, T4, and T12 locations to obtain spine kinematics. Load cells were used in the lower extremities to record impact forces. Pole-impact loads were recorded using a set of six uniaxial load cells. Accelerations of the vehicles were recorded using a uniaxal accelerometer placed at its center of gravity. The entire system of cameras, instrumentation, and floor-vehicle motions were synchronized using custom software, with the exception of the real time camera to obtain a panned view of the event. Interactions of the dummy head-neck-torso complex with the frontal impact airbag were evaluated along with timings of the initiation and full deployment using different camera views on a frame-by-frame basis. Loads and kinematics of the head-neck-torso and lower extremities, and deflection profiles at the four chest locations from the cruxes were evaluated with respect to the dummy motions.

III. RESULTS

(a) **Field data and injury analysis:** Eighty-four cases consisted of 52 males and 32 females; 79 survivors and five fatalities; 64 belted, 18 unbelted, and belt status was unknown in two occupants; frontal airbags deployed

in 77 cases, not deployed in four, and in the remaining three cases it was unknown; 47 and 37 cases were in the moderate (zone 2-5) and severe (zone 6-9) extent zone categories; 33 vehicle-to-pole/tree, 29 matched vehicle (car to car), 22 mismatched vehicle (car versus SUV) cases; and 55% of the vehicle model years were from 2000 to 2006. The average age, stature, total body mass, and BMI of the 84 occupants were: 41 years (standard deviation: ± 17 years), 1.72 ± 0 .10 m, 85 kg ± 21 kg, and 27.5 ± 7.7 kg/m^2. Seventy cases were classified as frontal plane crashes with a mean barrier change in velocity (output from WinSMASH software) of 30.6 ± 14.3 km/h. The mean curb weight of the case vehicle was 1460 ± 330 kg. Model years ranged from 1993 to 2006. The crush distance and extent zone demonstrated poor correlations ($r^2 < 0.02$) with injury severity. The injury severity scores ranged from 5 to 75, with a mean of 21 ± 14 for the entire ensemble. The injury severity for the thorax was similar between vehicle-to-pole and matched-vehicle impacts (ISS = 19 and 18), and was considerably greater (26) for mismatched vehicles. All five fatalities occurred in frontal plane crashes: head injuries occurred in four cases, thorax injuries occurred in three, and neck/cervical spine occurred in three cases (all AIS 4+); and all cases had traumas to more than one body region including the abdomen and extremities. In the remaining 65 survivors, according to AIS, injuries occurred to the head, face, thorax, abdomen, and spine regions in 18, 5, 20, 8, and 4 cases. Lower extremity injuries were common in fatal and non fatal groups. Head injuries were associated with contact within the vehicle components, assessments based on vehicle inspections, photographs, and medical records. The most frequent contact was attributed to the A-pillar.

(b) **Full-scale vehicle tests:** The as-tested vehicle weights were 1445, 1742, 1446, and 1268 kg, for the 2005, 2007, 2009, and 2010 vehicles, respectively. Chest deflections generally peaked approximately at the same time in each test; the right side of the chest of the dummy sustained greater deflections than the left side, and this was independent of the vehicle type. Increased belt tension lead to decreased upper neck shear forces, and greater shear force at the lower neck was associated with longer attainment times of peak belt tension.

In all tests the dummy responded with forward and outboard kinematics; duration of contact of the head-neck with the airbag directly influenced the lower neck flexion moment and upper left chest antero-posterior compression; and lateral chest deflection patterns at the upper level were symmetrical in both sides. No tests resulted in head to A-pillar contact, although the head-neck trajectories progressed toward this component from the initial position. A summary analysis of dummy loads is described in the preceding paragraph.

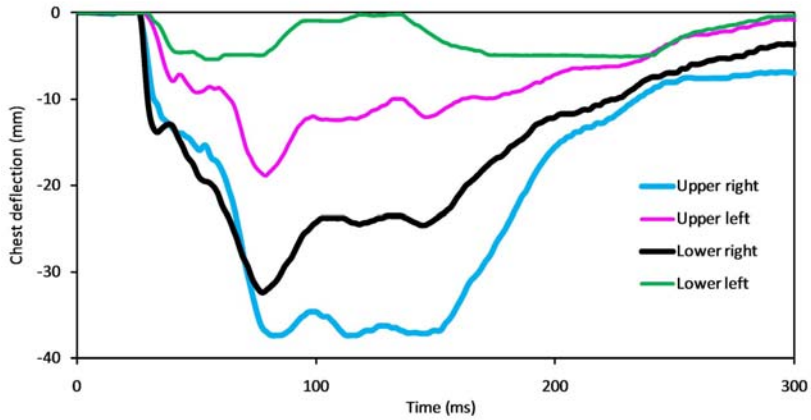

Figure 1: Chest deflections at four regions in the dummy from a full-scale vehicle small overlap impact test

Maximum chest compressions in the newer-body-structure (2009 model) vehicle was considerably lower than the companion older-body-structure (2005 model, compression-time histories shown in figure 1): upper right, upper left, lower right, and lower left deflections reduced to 17, 61, 31, and 74% in the newer-body-structure vehicle. The duration of the head-neck excursion was 22% shorter in the newer vehicle, and its airbag deployed later by 25 ms, took 11 ms less to fully inflate, and contacted the dummy for 48 ms less than the older vehicle. The upper neck shear and lower neck tension were reduced while upper neck tension stayed the same and lower neck tension increased in the newer-body-structure compared to the older-body-structure vehicles. In the full-size vehicle, the airbag interaction was minimal with the dummy essentially escaping the deployed airbag with an outboard translation of the head-neck complex prior to considerable thorax motion. In contrast,

in small vehicles, the dummy head interacted with the airbag, and head-neck kinematics was such that the head moved closer to the A-pillar during the impact phase. As indicated earlier, the head did not contact the A-pillar.

IV. Discussion

As injury data from the CIREN is non-population-based, it is not amenable to conventional statistical analyses. A limited number of full-scale vehicle tests were conducted. The THOR is not currently used in regulations in the world. While the Hybrid III dummy is widely accepted as the frontal impact device, it was not considered in the current tests because of its inability to measure multi-point deflections. Mid-sternum deflections do not best represent full occupant kinematics in small overlap impacts. Furthermore, the design of the THOR head-neck-torso based on more recent data better mimics the geometry and response of the human.

Acknowledging the above issues, forward and outboard motions of the THOR dummy characterize small overlap impacts, as this type of combined kinematics are, in general, in contrast to full frontal impacts wherein the motion is predominantly forward. Off-axis motions and loading contribute to the added severity of trauma. Changes in the design of the longitudinal members of the vehicle affecting the impact load (re)distribution alter the loading and kinematics of the dummy. These findings suggest that both sagittal and coronal plane kinematics contribute to increased traumas in small overlap impacts, and the vehicle structure also plays a role. Head contact observed in CIREN field data was not fully reproduced in full-scale vehicle tests although dummy kinematics was such that the head-neck complex moved towards the A-pillar in all cases. The THOR appears to be an appropriate dummy for these impacts because of its more human-like design including the anatomical rib cage and neck compliance. Furthermore, the presence of four crux potentiometers assisted in determining the chest deflections to characterize small overlap impacts. Small overlap impacts induce asymmetric loading and timings of attainments of peak deflections differ compared to full frontal impacts.

V. Conclusions

Emerging field data show injuries in small overlap impacts. Head contact occurs with the interior components such as A-pillar. Traditional crash metrics are inadequate descriptors of these crashes. Less than full structural engagement contributes to increased vehicle deformations, enhanced occupant motions, and injury susceptibility. Based on chest deflections and head-neck kinematics, the mechanism of head-torso injuries can be hypothesized to the asymmetric loading and kinematics of this complex, resulting in occupant motion towards the outboard side with less than optimal engagement with the airbag. Frontal impact airbag may not offer the most optimum protection in these crashes. As these small overlap impacts have not been systematically analyzed for injuries, injury mechanisms, occupant kinematics, and dummy measures such as multi-point sensing and head-neck trajectories and loads, the present study sheds light in all these areas.

VI. Acknowledgement

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