

ANALYSIS OF THORACIC LOADING, KINEMATICS, AND INJURIES IN SMALL OVERLAP IMPACTS: FIELD DATA AND FULL-SCALE VEHICLE TESTS WITH DUMMIES

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ABSTRACT

In the literature frontal crashes typically have been classified as full, large overlap, or small overlap impacts (SOI) in accordance with the degree of frontal area involvement. These classifications implicitly refer to the degree of longitudinal structure engagement during impact. While full and large overlap impacts have received considerable attention, SOI has undergone limited analyses through field and laboratory investigations. Limited structural engagements may expose occupants to increased intrusions and differing kinematics. The objective of this study was to summarize literature relevant to SOI, determine occupant injuries using CIREN data, and analyze occupant loading and motions using full-scale vehicle tests. CIREN results demonstrated lack of correlation between injury and typical crash severity parameters of ΔV , crush distance, and extent zone. Full-scale crash tests suggested that occupant kinematics in SOI may be unique among frontal impact configurations.

INTRODUCTION

Since the 1960's, traffic death rates have steadily declined in the United States. The National Highway Traffic Safety Administration (NHTSA) reported that traffic deaths per 100 million vehicle miles traveled fell from 5.5 to 1.13 between 1966 and in 2009 [1]. This decline may be attributed in part to advances in vehicle crashworthiness in frontal impacts, which remain the most common vehicle crash mode [1]. These advances were catalyzed in large part by consumer crash test programs such as those performed by the Insurance Institute for Highway Safety (IIHS) and the New Car Assessment Programs (NCAP) conducted by numerous governments. These tests evaluate occupant protection during impact into a fully-engaged flat rigid barrier (US-NCAP) or into a deformable barrier with 40% frontal width engagement (IIHS, EuroNCAP). Between 1979 and 2007, vehicles rated in frontal impact by

US-NCAP at four and five stars (max = five) increased from less than 30% of models tested to greater than 98% [2]. Between 1995 and 2009, tested vehicles achieving the highest IIHS frontal impact rating increased from less than half to 91% [3].

Vehicles performing well in NCAP and IIHS tests are typically designed with energy-absorbing structural members oriented longitudinally (Fig. 1) [4]. These longitudinal members lie bilateral to the powertrain (for front-engine configurations) and inside of the front wheel track and suspension components. During full and 40% frontal width engagements, at least one of these energy-absorbing components is loaded, dissipating crash energy and transferring it around the occupant compartment.

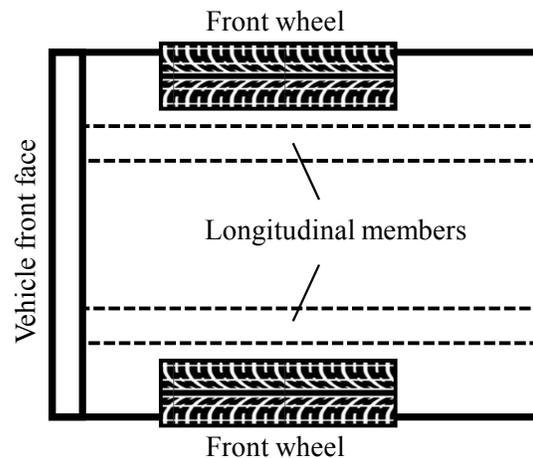


Figure 1. Vehicle overhead view demonstrating orientation of longitudinal structural members.

As a consequence of crashworthiness improvements in these crash scenarios, the small overlap impact (SOI) has emerged recently as the frontal crash mode of greatest risk to vehicle occupants. A recent report by NHTSA cited SOI as the most common scenario of preventable mortality amongst frontal impacts in

the National Automotive Sampling System / Crashworthiness Data System (NASS/CDS) during 2000-2007 [5]; these deaths occurred despite correct belt restraint usage and airbag deployment. Lack of structural engagement was cited as the primary factor leading to fatality in these crashes. Therefore, the objective of the present study was to distill current advances with regard to SOI through an examination of preexisting literature, recent CIREN injury data, and vehicle crashworthiness experiments.

LITERATURE

Using a collection of German crash data collected over a 20 year period, 502 crashes were found to result in injury [6]. Of these crashes, 62% corresponded to frontal impacts; 75% of these could be classified as partial overlap loadings, i.e., less than 50% frontal width engagement. Examination of this same dataset by another study revealed that 26% of frontal impacts were characterized by $\leq 30\%$ frontal width overlap [7]. Structural involvement characteristics were not reported, but a companion study described the structural modifications necessary to protect occupants when frontal width engagement was 40% or less [8]. The authors noted that these improvements, particularly occupant compartment stiffening, also may contribute to improved protection in more severe impacts, i.e., narrower overlap.

A sample of 1,872 frontal crashes in England between 1983 and 1990 was examined for vehicle damage and occupant injuries [9]. The authors defined SOI as an impact with less than 60% frontal width overlap (less than 45% when impacting rigid objects) and only one longitudinal member engaged. Comparing injuries to averages for all frontal crash modes, belted occupants in SOI crashes sustained higher incidences of head (66 vs. 58%), neck (24 vs. 22%), and thigh (53 vs. 43%) injuries. Occupants in SOI crashes sustained decreased incidence of torso injuries (66 vs. 69%). Yet, the authors' definition of SOI allowed for engagement of one structural member. This definition may more resemble the current IIHS test configuration.

Crash data from 52 fatal accidents in Great Britain were examined specifically for structural engagement [10, 11]. It was reported that in 25 cases (48%) only one longitudinal member was loaded. Yet, in 18 cases (36%) no major structures were fully engaged; in 4 of these cases one longitudinal member was considered to be partially loaded. A 40% frontal width overlap test with deformable barrier was recommended; this boundary condition was designed

to avoid engine block engagement, forcing energy transfer through the vehicle structural components.

Using a primarily Swedish dataset of crashes involving Volvo automobiles, frontal impacts were found to compose 36% of crashes [12]. SOI impacts, termed severe partial overlap collisions, were defined by less than 50% overlap, principal direction force (PDOF) = $0^\circ \pm 30^\circ$, and "extensive deformation." When SOI crashes were parsed from other crash types, e.g., frontal, side, rollover, etc., they composed 3% of all crashes but 14% of accidents with AIS 2+ injuries. Crash tests into a rigid barrier with 35% frontal width engagement were proposed to replicate case observations.

Many studies have utilized the Collision Deformation Classification (CDC) published by the Society of Automotive Engineers [13]. The CDC represents a standardized seven digit alphanumeric code describing the crash direction (PDOF), general area of involvement, horizontal and vertical regions of direct damage, type of damage distribution (e.g., wide impact area or sideswipe), and deformation extent into vehicle structure (Fig. 2). With regard to horizontal region of direct damage, the CDC documents the degree of frontal width involvement using three equal segments (Left, Center, and Right); documentation indicates segment(s) included, i.e., when direct damage is less than one-third, between one-third and two-thirds, or greater than two-thirds frontal width (Fig. 3). Further information is obtained from the type of damage distribution (Table 1) and the extent zone (Fig. 4). Information regarding vehicle structural engagement is not included explicitly in the CDC.

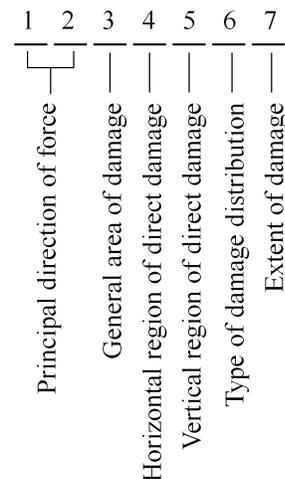


Figure 2. Collision Deformation Classification (CDC) system format.

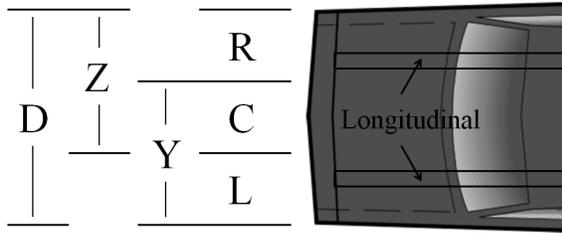


Figure 3. Relevant CDC codes with regard to horizontal region of direct front damage.

Table 1. Types of damage distribution in CDC.

Type	Code	Engagement
Sideswipe	S	Corner, ≤ 10 cm
Corner	E	Corner, 10 - 41 cm
Narrow Impact	N	< 41 cm
Wide impact	W	≥ 41 cm
Overhanging	A	Inverted step
Conversion	K	>1 type
Unknown	9	-

Using 1990-92 NASS data and CDC codes, 46% of frontal impacts were found to involve greater than 2/3 frontal area [14]. Of the remaining crashes, 20% involved less than 1/3 frontal area and 32% involved between one-third and two-thirds frontal area. To simulate a collinear two-vehicle impact with 50% frontal width overlap, vehicles were tested with a deformable barrier and frontal overlaps of 50% ($n = 3$), 40% ($n = 8$), and 30% ($n = 2$). While resulting structural engagement was not described; the authors noted that the CRASH3 algorithm, which estimated crash ΔV from vehicle crush, was inappropriate for the two vehicles tested with 30% overlap.

Following the introduction of vehicles which performed well in partial overlap deformable barrier impacts, field analyses reexamined the real-world performance of the new fleet. In place of the generalized CDC, a systematic analysis of structural components was proposed [15] and applied to a Swedish dataset of 53 fatal crashes involving 61 belted occupants [16]. In 20 of these crashes, no longitudinal members were loaded. Moreover, the most commonly reported load paths were the left side structure (e.g., door hinge), left wheel, and left shotgun beam. When these load paths were expressed as CDC codes, more than 45% of fatal crashes engaged less than one-third of the vehicle frontal width.

The relationship between injured body region and frontal crash type was examined using an Australian dataset containing 119 frontal impacts [17]. Frontal impact type was stratified according to the CDC;

narrow and wide overlap crashes were characterized by frontal width damage less than one-third or two-thirds, respectively. Narrow overlap composed 26% of frontal impacts; wide overlap composed 29%. Compared to fully distributed impacts, narrow and wide overlap crashes were more likely to result in MAIS 2+ injury to face, abdomen/pelvis, and lower extremities.

The relationship between injured body region and crash type was examined with US data contained in the NASS/CDS (2000-2006) and Crash Injury Research and Engineering Network (CIREN) database [18]. Only narrow overlap crashes were considered and were identified by CDC codes “FLEE” and “FREE” indicating involvement of the left or right one-third frontal width only. Damage type was also limited to corner impacts (Table 1). For CIREN cases, photographic documentation was reviewed to confirm no longitudinal member engagement. It was found that lower extremity injuries were most frequently reported, followed by head, chest, and pelvis injuries. Increased injury incidence was not consistently associated with increased occupant compartment intrusion, suggesting that occupant kinematics may play a unique role in SOI injury mechanisms.

A similar NASS/CDS study examined SOI crashes and injuries [3]. The authors highlighted the complexity in categorizing this crash mode using the CDC syntax. Therefore the CDC inclusion criteria were expanded to include impacts which may appear initially to be lateral impacts. Head, neck, thorax, and lower extremity injuries were most common, and a positive relationship we observed between occupant compartment intrusions and injury severity score (ISS).

The most sophisticated SOI definition to-date was recently published in the SAE Congress Proceedings [19]. This definition builds upon a previous refinement of the CDC [20] and utilizes CDC codes, damage measurements, and estimated structural geometry of the case vehicle to identify SOI frontal impacts which likely do not involve longitudinal member engagement. Both frontal and side impacts are considered by the algorithm, and structural geometry is estimated by published data for each vehicle weight- and body-class.

These previous studies demonstrated that continued work is necessary to reduce injury and mortality risk from frontal impacts. The subset of SOI may be most relevant to continued improvements, yet injury patterns and mechanisms have not been consistently

established. Further improvement to SOI crashworthiness therefore requires enhanced understanding of structural interactions and vehicle/occupant kinematic response to SOI loading.

METHODS

The present study examined occupant injury outcomes and biomechanical dummy responses in real-world and laboratory SOI impacts. Injury outcomes were obtained from real-world SOI crashes contained in the CIREN database of US crashes. Biomechanical dummy responses were measured during four full-scale small overlap crashworthiness tests.

Database Query

The CIREN database was queried manually for incidence of SOI. The CIREN database, formed in 1996, is a collaboration of clinicians and engineers at up to twelve Level 1 Trauma Centers in the US. Enrolled cases generally involve AIS 3+ (or multiple AIS 2) injuries occurring in late model vehicle crashes. SOI was identified by vehicle damage photography and CDC information. Vehicle data were examined for collision partner, extent zone, and crush distance. Occupant data was examined for seat position, gender, age, and ISS.

Vehicle Crash Tests

Four vehicle crash tests were conducted at the MCW Vehicle Crashworthiness Laboratory (Table 2). All vehicles were equipped with belt pretensioners and load limiters for the front seat occupants. For the third and fourth tests, vehicle make and model were identical but, in the latter test, the vehicle structure was advertised to promote greater structural engagement during diverse frontal impact configurations. SOI was simulated by positioning each vehicle on a movable test platform incident upon a rigid pole fixture with 25 cm diameter (Fig. 4). In each test, the vehicle was positioned on the movable test platform such that the left outside track width was aligned with the outboard margin of the pole fixture. Vehicle impact angle was adjusted such that the center of the occupant head in the driver position was aligned with the center of the pole fixture. Nominal impact velocity was 56 km/h.

For each test, a fiftieth percentile THOR anthropomorphic test dummy was belted in the driver's seat position. The dummy was equipped with instrumented chest crux arms to measure anterior chest deflections in four quadrants (Fig. 5): upper left (UL), upper right (UR), lower left (LL),

and lower right (LR). The shoulder belt was positioned such that it overlaid the UR crux and passed superior to the LR crux. Deflections were examined in time domain and compared between test vehicles.

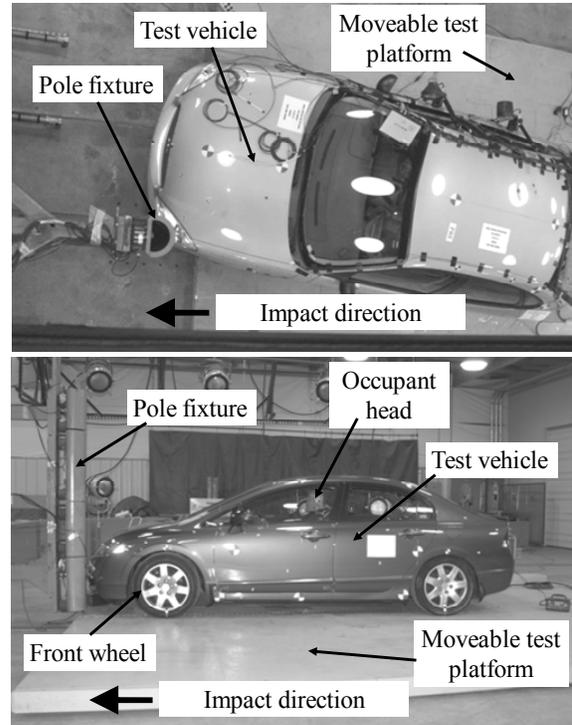


Figure 4. Setup for vehicle SOI test.

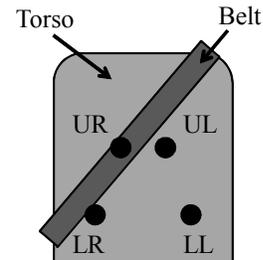


Figure 5. THOR crux locations with respect to belt pretest positioning, viewed from anterior.

Table 2. Description of test vehicles.

Test	Model year	Class	Weight (kg)	Structure
1	2006	Mid-sized	1742.7	Normal
2	2010	Sub-Compact	1268.2	Normal
3	2005	Compact	1445.6	Normal
4	2010	Compact	1446.0	Enhanced*

* As advertised by manufacturer

RESULTS

Database Query

CIREN case query identified 82 crashes which could be categorized as SOI; a typical post-crash vehicle photograph is shown in Figure 6. In each crash, photographs and PDOF determination clearly demonstrated a front corner contact without longitudinal member engagement of the vehicle. These crashes were subcategorized by collision partner: vehicle-to-pole impacts (n = 34), matched-vehicle impacts (n = 25), and mismatched-vehicle impacts (n = 23). A mismatched vehicle pairing was defined as an impact in which the case vehicle weight was substantially less than that of the striking vehicle weight.

Among the 82 cases obtained, occupant and occupied vehicle characteristics are shown in Figure 7. Vehicle drivers represented the majority of case occupants. Additionally, males and younger ages represented a greater proportion of the dataset. The vast majority of vehicles were passenger cars.

Average ISS are shown in Figure 8 with respect to SOI subcategory. Mismatched vehicle impacts demonstrated the greatest average ISS, followed by vehicle-to-pole impacts. Matched vehicle impacts demonstrated the least average ISS but still exceeded 15, considered to be the threshold for severe (poly)trauma [21].

Intrusion was quantified both by crush distance into the vehicle and by deformation extent (Figs. 9 and 10). Extent zones between 2 and 5 represented “moderate” crush and extent zones 6 through 9 represented “severe” crush. Of 82 CIREN cases, 38 (46%) represented moderate crush; 32 (39%) represented severe crush. To identify the relationship between injury and indicators of crash severity, linear correlations were calculated between ISS and parameters of ΔV , crush distance, and extent zone. As demonstrated by Table 3, ISS was not correlated with these indicators of crash severity in SOI crashes.

Thorax injuries in CIREN cases also exhibited posterior rib fractures (Fig. 11). Because prior research has suggested anterior and right lateral fractures to result from restraints and/or steering wheel during structurally-engaged frontal impacts [22], these injuries suggested altered occupant kinematics during SOI. Therefore, attention was given specifically to the biomechanical response of the THOR thorax in the full-scale SOI crash tests.

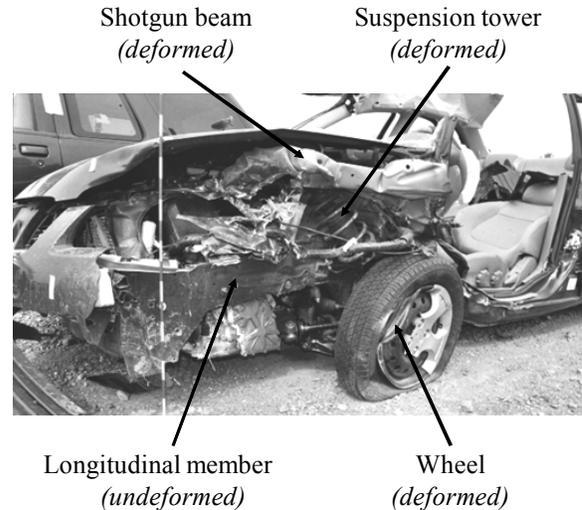


Figure 6. Typical CIREN case demonstrating SOI characteristics.

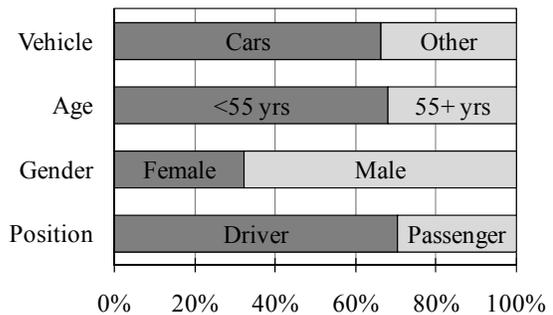


Figure 7. CIREN case distribution of occupant characteristics.

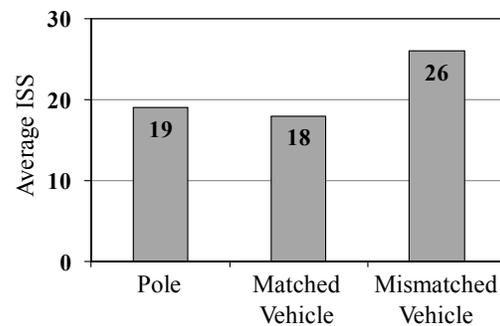


Figure 8. ISS with respect to SOI crash partner.

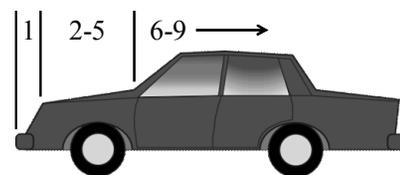


Figure 9. CDC extent zones relevant to SOI.

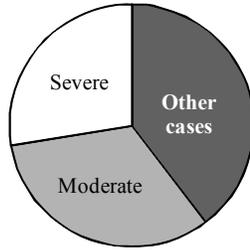


Figure 10. Distribution of SOI cases by extent zone category.

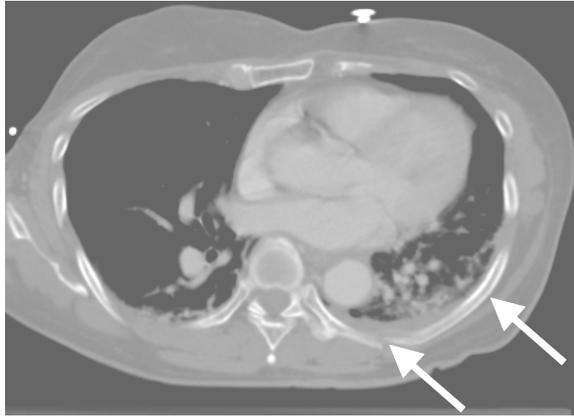


Figure 11. Exemplar posterior rib fracture pattern for SOI.

Table 3. Linear correlations with ISS.

Parameter	R ²
ΔV	0.0603
Crush distance	0.0988
Extent zone	0.0001

Vehicle Crash Tests

Final impact velocities of the four crash tests ranged from 56.0 km/h (Test 4) to 56.3 km/h (Test 3). Tests 1 and 2 both achieved 56.1 km/h. Resulting vehicle deformations were similar to case observations within the CIREN database (Fig. 12). Namely, lateral suspension and shotgun beam components were deformed, and the left front wheel was sheared away from the vehicle. The left longitudinal member remained undeformed as could be determined by visual inspection.

Deflections from the THOR dummy were examined in the time domain (Fig. 13). Time zero represented vehicle-pole contact. For all tests, resultant deflections were initially greatest at the LR crux. Later in impact progression the LR deflections were surpassed by UR; time at which this occurred ranged from approximately 75 ms (Test 4) to greater than

100 ms (Test 2). Examination of onboard videography suggested that deflections resulted both from belt loading due to vehicle deceleration and chest contact with the steering wheel and airbag. Chest contact was particularly prominent for Test 2, in which the dummy demonstrated substantially greater deflection response early in the impact progression. Particularly, both UL and LR cruxes deflected sharply at onset. Videographic documentation suggested the occupant of this subcompact vehicle may have contacted the steering wheel at this time. In all tests deflection responses appeared complex, with right side deflections generally exceeding left side deflections. Further, LL deflections were positive in three of four tests, indicating an exaggerated asymmetric chest loading.

Peak chest deflection values are contained in Table 5. In three of four tests, overall peak deflection was obtained from the UR crux. Comparing tests 1 and 2 (full-size vs. small car), an inverse relationship between vehicle mass and chest deflection was suggested. Recall that tests 3 and 4 represented similar vehicle make/model; the latter test represented a vehicle with structural design advertised to enhance structural engagement during a diverse set of frontal impact scenarios. Comparing THOR response between the occupants of these vehicles, structural modifications may have reduced chest deflections.

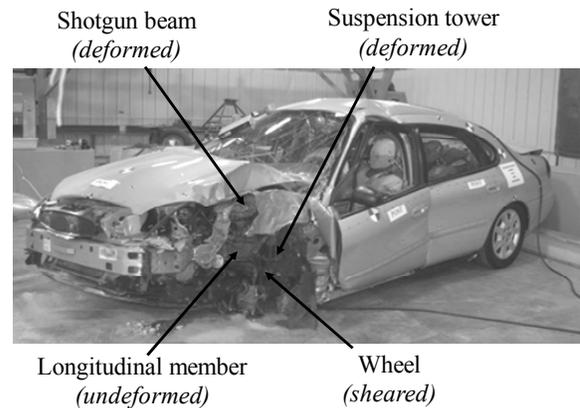


Figure 12. Exemplar deformation from SOI crash tests.

DISCUSSION

Distributed and wide overlap crashes (i.e., 40% frontal width) have received substantial attention with regard to research, testing, and resulting vehicle crashworthiness improvements. Consequently SOI crashes have emerged as a frontal impact mode posing great risk to properly restrained vehicle occupants.

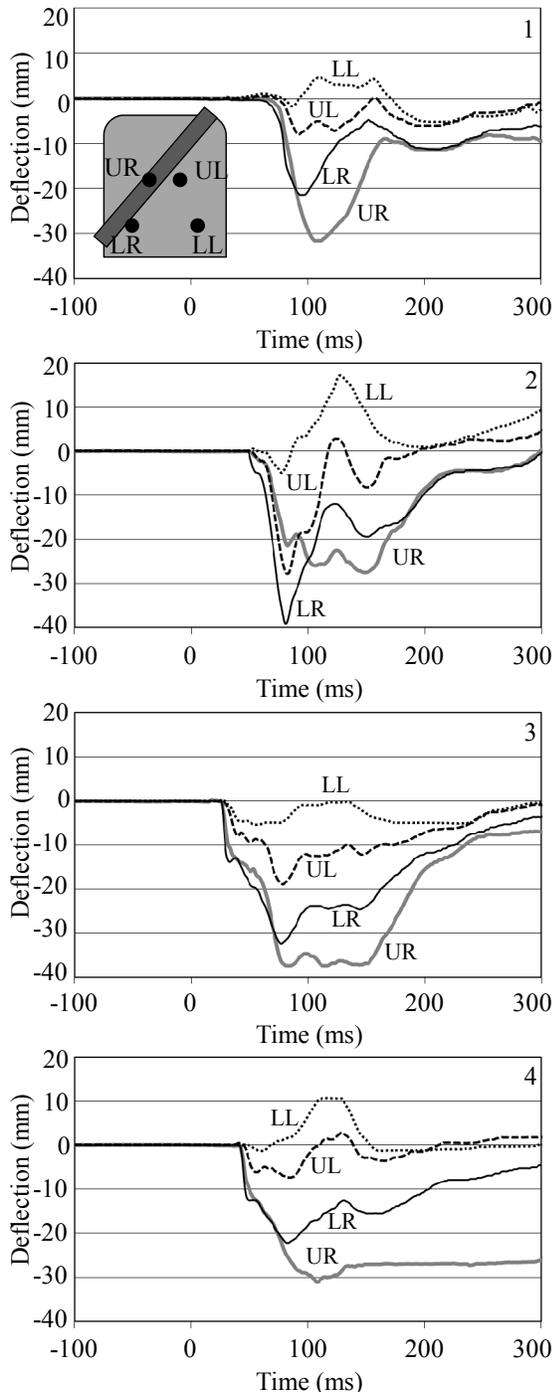


Figure 13. THOR chest deflections from four SOI vehicle tests.

Table 5. Peak THOR chest deflection results from four SOI tests (mm).

Test	UL	UR	LL	LR
1	8.0	31.6	5.3	21.5
2	27.8	27.6	5.0	39.2
3	18.9	37.4	5.4	32.4
4	7.4	31.2	1.4	22.2

This study examined this crash mode through a review of published literature, injury observations in the CIREN database, and four full-scale SOI vehicle tests.

Although many studies have emphasized the role frontal engagement plays in frontal impact injury outcomes, consistent definitions of SOI have not been utilized. In prior studies, reduced overlap crashes have been considered “small” when estimated frontal width engagement was below specified thresholds; these thresholds were suggested anywhere from 60% [9] to less than 33% and less than 41 cm (16 inches) [18]. With continued examination of real world crash data, inclusion criteria were expanded to include impacts with CDC codes indicating side impact [3, 19]. Wide acceptance of a common SOI definition will enhance the utility of field data for statistical analyses of injury outcomes.

Existing CIREN data demonstrated a lack of correlation between injury severity and vehicle intrusion (deformation extent or crush distance) or ΔV . This may be explained in part by the inconsistencies between small overlap crash tests and ΔV algorithms [14]. Contributing to the SOI injury mechanism may be altered occupant kinematic response; this was suggested by posterior rib fractures in CIREN cases.

Altered occupant responses were observed in four vehicle crash tests. Specifically, peak deflections were observed to transition from UL to UR cruxes with opposite LL crux response polarity. This suggested that concentrated belt loading was shifting across the thorax with time, resulting in an exaggerated asymmetric response. This may also suggest that occupant kinematics are altered by SOI such that the occupant no longer receives maximum benefit from the restraint system.

In response to studies of vehicle crashworthiness compatibility [23, 24], automotive manufacturers have proposed modifications to enhance structural engagement and control crash load paths during impact. For example, the Honda Advanced Compatibility Engineering (ACE™) body structure includes structural components outside of the traditional longitudinal members [4]. Although not yet evaluated in SOI, structural modifications such as these were suggested by the present study to improve occupant safety in SOI.

CONCLUSIONS

Until recently, SOI crashes have received little attention compared to frontal impacts with distributed or wide overlap frontal engagement. Although the standard SOI definition, i.e., no longitudinal member engagement, is difficult to query from common crash databases, an operational SOI definition is developing. CIREN analysis found that injury severity may not be related to common indicators of crash severity, suggesting that altered occupant kinematics may contribute to SOI injury mechanisms. Four full-scale crash tests supported this hypothesis.

ACKNOWLEDGMENTS

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