Identifying Thoracic Injury Factors by Comparing Rib Fracture Patterns in Field Crashes and PMHS Sled Tests

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Abstract Recent studies indicate real-world thoracic injury in frontal crashes is not well-predicted by anthropometric test devices (ATDs) in crash tests. Comparing the location of rib fractures in post-mortem human subject (PMHS) tests directly with field crash outcomes could highlight real-world injury mechanisms, which ATD metrics may be insensitive to. The distribution of fractures sustained by drivers ages 50 and older restrained by a seat belt and front airbag were compared with the PMHS fractures in previously published literature. Fractures were also stratified by the total number of fractured ribs, PMHS restraint type, and characteristics of the field crash, vehicle, and occupant. Results indicate significant differences in the distribution of ribs most often fractured in crashes and PMHS tests. Drivers were more likely than PMHSs to have fractures that were both inboard and inferior on the thorax. PMHSs with outcomes most similar to field crashes were restrained by a seat belt and airbag without a knee bolster. This and other findings suggest most real-world rib fractures result from occupant kinematics characterised by pelvis excursion more than forward pitch of the torso. Countermeasures that focus more restraint load on the superior outboard ribs have the potential to reduce real-world thoracic injury risk.

Keywords crashworthiness, frontal crashes, PMHS, thoracic injury.

I. INTRODUCTION

Despite overall progress in front crashworthiness of the passenger vehicle fleet [1–3], serious thoracic injury risk has not decreased [4]. There is some indication that real-world thoracic injury risk for drivers restrained by a seat belt and airbag is better predicted by peak shoulder belt tension measured in crash testing than by injury measures recorded using Hybrid III or the Test Device for Human Occupant Restraint (THOR) [5–6]. This raises the question of whether these anthropometric test devices (ATDs) are sensitive to the predominant injury mechanisms in real-world crashes. While peak Hybrid III and THOR chest deflections have been shown to predict post-mortem human subject (PMHS) injuries to a similar degree [7], many of the PMHS tests used for comparison involve conditions that do not represent modern vehicle restraint systems. Even in representative conditions, it is unknown to what extent PMHS injury mechanisms represent those in the field. At the same time, PMHS testing has the potential to isolate the effect of countermeasures in a way that could highlight the most important restraint design strategies. Direct comparisons of injury between PMHS tests and field crashes do not require the use of intervening measures, e.g., chest deflection, or tools, e.g., ATDs, but the results could be useful as part of ongoing efforts to improve the real-world relevance of crashworthiness measures and tools. The number and location of fractured ribs has been documented in both PMHS tests and real-world crashes, providing a direct means of injury comparison.

Several previous studies have analysed the locations of rib fracture in field crashes or PMHS tests without making direct comparisons. Reference [8] compared rib fracture locations for 14 PMHSs restrained by a seat belt with 15 PMHSs restrained by a seat belt and airbag. They found tests without an airbag resulted in fractures that were generally along the belt path, with outboard superior and inboard inferior ribs most likely to be fractured. The addition of an airbag produced fractures that were more evenly distributed laterally and vertically. Two studies of frontal crashes [9–10] found rib fracture location differs by front crash overlap, with near-side small overlap crashes producing more fractured ribs on the outboard side of the thorax, while crashes with more overlap result in a similar [9] or greater [10] proportion of inboard fractures. Reference [11] evaluated front-seat occupants involved in frontal crashes from the Crash Injury Research Engineering Network (CIREN). All occupants were restrained by a deployed airbag, but some were unbelted. The authors found differences in the distribution

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of fractured ribs by belt use, with belted occupants sustaining more inboard rib fractures and unbelted occupant fractures more evenly distributed. One previous study [12] did include a chart with fracture locations from the 15 PMHS airbag tests reported in [8] and from 51 CIREN crashes with a principal direction of force (PDOF) of 11–1 o'clock, but the differences were not discussed other than noting the field crashes produced more lateral and posterior fractures.

The current research comparing rib fracture outcomes in PMHS tests and field crashes involves two stages. First is the identification of factors that contribute to injury in the set of PMHS tests under evaluation. This is independent of any field data but is necessary to be able to distinguish between effects that reduce injury severity and those that simply result in different ribs being fractured. This first phase was performed and described separately [13]. PMHS tests with conditions most similar to modern vehicle restraint systems were identified and logistic regression was used to evaluate the effect of different test, subject, and restraint system variables on injury outcome. Injury was assessed using the number of fractured ribs (NFR), with various NFR threshold levels used to define the binomial outcome. Among other findings, the presence of an airbag and knee bolster were both associated with reductions in the risk of NFR≥7, where 7 was the median NFR in all PMHS tests.

This study comprises Phase II of this research. The distributions of fractured ribs in field crashes and PMHS tests are used to assess the most likely injury mechanisms in real-world crashes as well as the degree to which existing PMHS sled tests replicate the field crash data.

II. METHODS

Field Crashes

Field crash data were obtained from the National Automotive Sampling System-Crashworthiness Data System (NASS-CDS) and its replacement, the Crash Investigation Sampling System (CISS). These databases are maintained by the National Highway Traffic Safety Administration (NHTSA) and comprise an annual sample of tow-away crashes in the US. They were queried for belted drivers aged 50 or older [5] who were involved in a frontal crash (defined as *GAD1 = F* in NASS-CDS and *CDCPLANE = F* in CISS for the most severe event) in which the steering wheel airbag deployed. Drivers were included if they sustained at least one fracture of ribs 1–10. Calendar and model years were restricted to 2005 and later. While comparisons with the field data were restricted to ribs 1–10, fractures of the sternum, clavicles, and ribs 11–12 also were recorded.

Frontal crashes that met the above conditions were reviewed photographically to determine vertical and horizontal overlap, obliquity [9–10] and intrusion severity. Crashes that involved underride or that had instrument panel, A-pillar, or steering wheel intrusion levels greater than those observed in the Insurance Institute for Highway Safety (IIHS) moderate-overlap test were excluded from further analysis. Other crashes were categorised into three overlap and three obliquity groups. Overlap groups were near-side small overlap, far-side small overlap, and *moderate+* overlap, which consisted of moderate overlap, large overlap, and centre impacts. Obliquity groups consisted of oblique from left, oblique from right, and collinear. Table AI in the Appendix contains examples of each overlap and obliquity category.

PMHS Tests

PMHS sled tests were identified from the literature and the biomechanics test database maintained by NHTSA. Inclusion criteria were selected to ensure the resulting test conditions were relevant to modern vehicle restraint systems. The inclusion criteria were: pure frontal sled pulse (non-oblique); three-point belt restraint with peak shoulder belt tension < 6 kN; no contact between PMHS head or torso and any vehicle component other than an airbag; no autonomous-vehicle reclined-seat tests; no belt geometry designed to induce submarining; no PMHS fractures from previous testing of the same subject; no PMHS fractures attributed to instrumentation; and at least one fracture of any non-floating rib (ribs 1–10). Table AII in the Appendix lists the 86 PMHS tests that met these criteria. These are a subset of the tests included in Phase I of this research [13] since, for that analysis, documentation of the specific ribs fractured was not required, and tests that produced no rib fractures were included. Rib locations for tests conducted with a right seat were transposed to represent the belt geometry of a driver seat in a left-hand drive vehicle. As with the field crashes, other thoracic fractures were recorded but not included in comparative analyses.

Comparative Analysis

Rib fracture locations in PMHS tests and field crashes were compared graphically and quantitatively. Graphical comparisons were performed by plotting the number of fractured ribs relative to the rib that was most often fractured. This produced a visual heat map of fracture locations that can be compared across subject or crash types, even when the overall proportion of subjects that sustained a fracture differed. Individual PMHS ribs with multiple documented fractures were only counted once.

Quantitative comparisons of rib fracture locations were performed by counting the proportion of fractured ribs that occurred in different rib groups. Ribs were grouped laterally (inboard vs. outboard) and vertically (ribs 1–5 vs. 6–10 and ribs 1–3 vs. 4–10). Nonparametric bootstrapping was used to calculate group means, confidence intervals, and to compare differences between groups. Preliminary analyses showed only minor differences between bootstraps formed by resampling 10,000 times. To be conservative, the final analyses used bootstraps formed by resampling 50,000 times. The 2.5%ile and 97.5%ile values for each group were used to construct 95% confidence intervals. Similarly, 95% confidence intervals for the differences between groups were constructed using the 2.5%ile and 97.5%ile values for the differences in group means. The $\alpha = 0.05$ level was chosen to define statistical significance, or when the 95% confidence interval for the difference in group means did not include zero.

In addition to comparisons between all PMHS tests and field crashes, subsets of the tests and crashes were evaluated. Several subsets were based on factors that have the potential to change the distribution of rib fracture locations or which previously have been found to correlate to injury outcome. In Phase I of this research [13], the presence of a knee bolster and/or airbag in belted PMHS testing was correlated with a reduction in NFR. These restraint system countermeasures were used to stratify the PMHS tests for comparison with field crashes, with restraint groups referred to as airbag only (AB), knee bolster only (KB), both (AB+KB) and neither (noAB/KB). In addition, as a measure of injury severity, PMHS tests with a delta-V of 45 km/h or greater were stratified into two groups: those resulting in less than the median NFR and those with a number greater than or equal to the median. Field crashes were categorised based on front overlap, obliquity, driver age, sex, body mass index (BMI), vehicle type (car vs. light trucks and vans [LTVs]), the type of lap belt pretensioner, and the maximum shoulder belt load measured in matched US New Car Assessment Program (NCAP) front crash tests. Three NFR groups were also defined to yield roughly equal numbers of drivers in each group.

III. RESULTS

There were 190 NASS-CDS and CISS cases that met inclusion criteria, 64% of which were categorised as collinear crashes with moderate overlap, large overlap, or centre impact loading (*moderate+*). The remainder were either small overlap crashes or crashes involving oblique loading. Figures 1 and 2 show the rib fracture locations by overlap and obliquity, respectively. Given the differences, only the 121 collinear moderate+ overlap crashes were used in the comparisons with PMHS sled tests and in the analysis of occupant and vehicle factors. Figure 3 shows the ribs fractured by total NFR for three groups. There were 86 PMHS tests with known rib fracture locations available for analysis. Summary metrics for drivers in collinear moderate+ crashes and PMHS are shown in Table 1. The driver and PMHS samples were 53% and 45% female, respectively. Summary metrics for the small overlap and oblique crashes, as well as PDOF values for all configurations are given in the Appendix (Table AIII and Fig A1).

An overall comparison of rib fracture locations in field crashes and PMHS tests is shown in Figure 4. Relative to the PMHS results, ribs fractured in real-world crashes were more often on the inboard side and inferior on the thorax. Knee bolster and airbag presence was associated with a difference in the distribution of ribs fractured in the PMHS tests (Fig. 5), with the biggest differences observed between PMHSs restrained with only one or the other (AB or KB), while the PMHSs restrained with both an airbag and knee bolster (AB+KB) had a similar distribution of fractured ribs to the PMHSs tested without either one (noAB/KB).

A bootstrapping process was used to estimate the proportions of fractured ribs in different categories. Figure 6 displays the results of comparisons between field crashes and different groups of PMHS sled tests, while Figure 7 shows differences based on different field crash characteristics. While non-overlapping 95% confidence intervals (CIs) indicate the estimated difference in means is statistically significant at $\alpha = 0.05$, overlapping CIs do not guarantee nonsignificance of the estimated difference. In several cases, estimated proportions were significantly different despite overlapping CIs in Figures 6 and 7; these are listed in the Appendix.

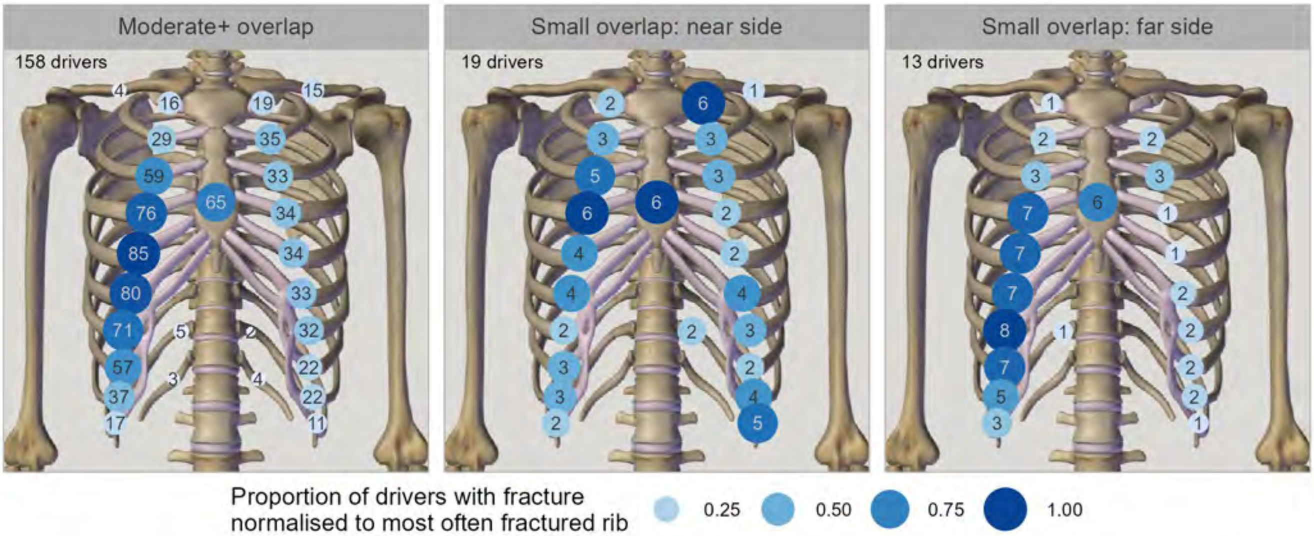

Fig. 1. Fractured ribs in field crashes by overlap. "Moderate+" includes moderate overlap, full overlap, and centre impacts.

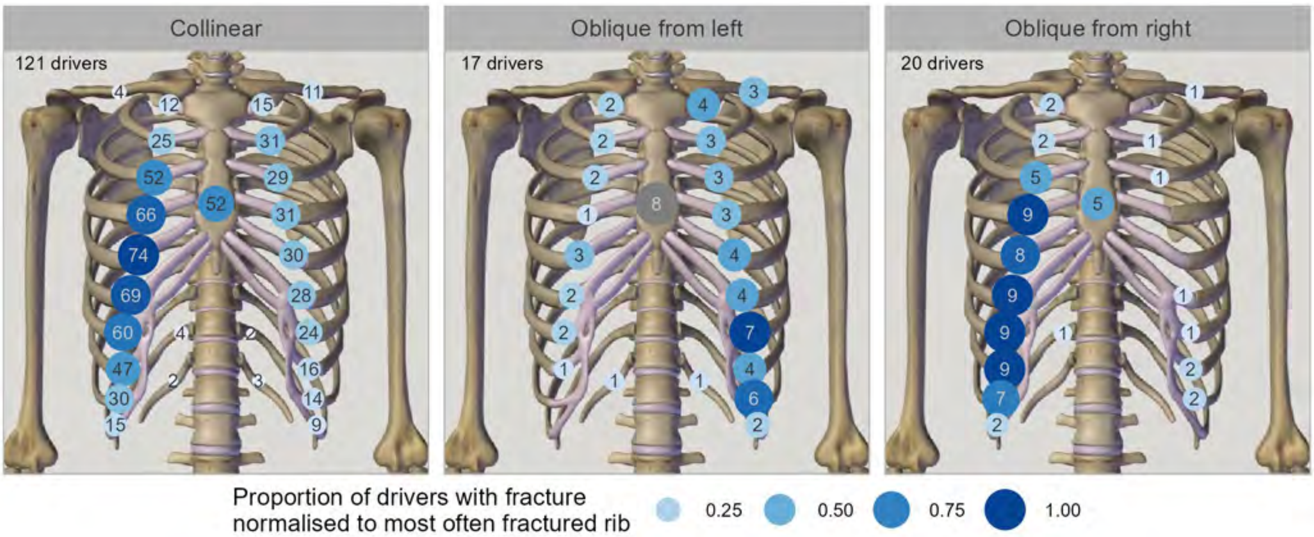

Fig. 2. Fractured ribs in moderate+ field crashes by obliquity.

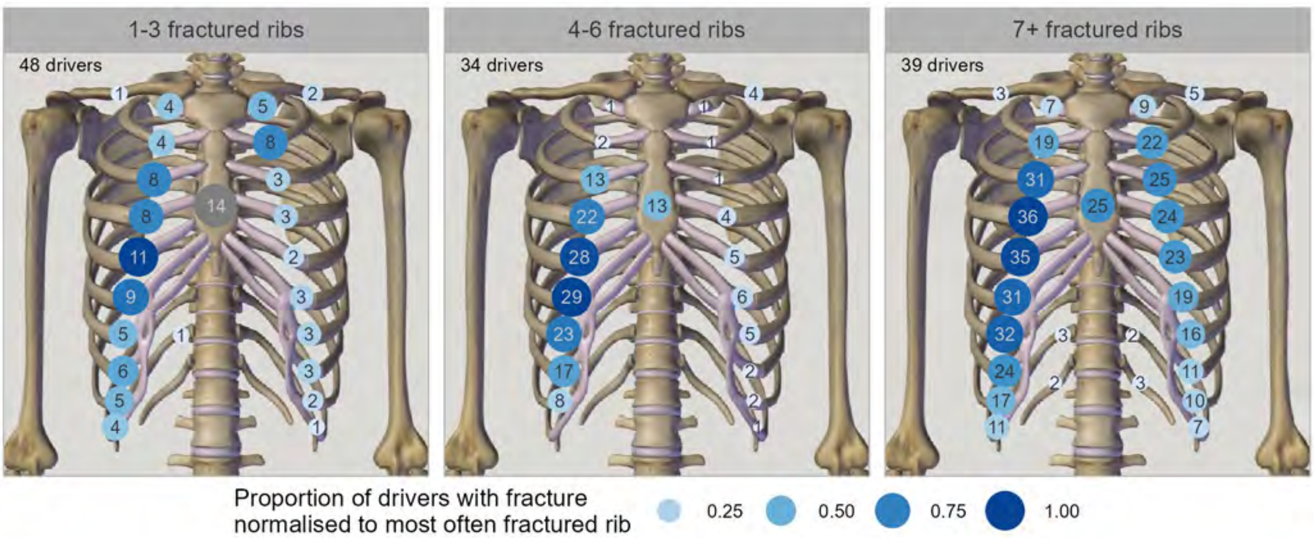

Fig. 3. Fractured ribs in collinear moderate+ overlap field crashes by total number of fractured ribs per driver.

TABLE I
SUMMARY METRICS

	Drivers (n = 121)				PMHS (n = 86)		
	Unk.	Min	Max	Median	Min	Max	Median
Age (years)	0	50	88	67	46	92	69
Stature (cm)	19	140	198	168	144	190	167
Mass (kg)	12	41	159	80	35	134	62
BMI (kg/m^2)	19	16.0	58.4	28.7	14.4	45.8	21.8
Fractured ribs	0	1	20	5	1	19	7

Note: Unk. = unknown; there were no unknown PMHS values.

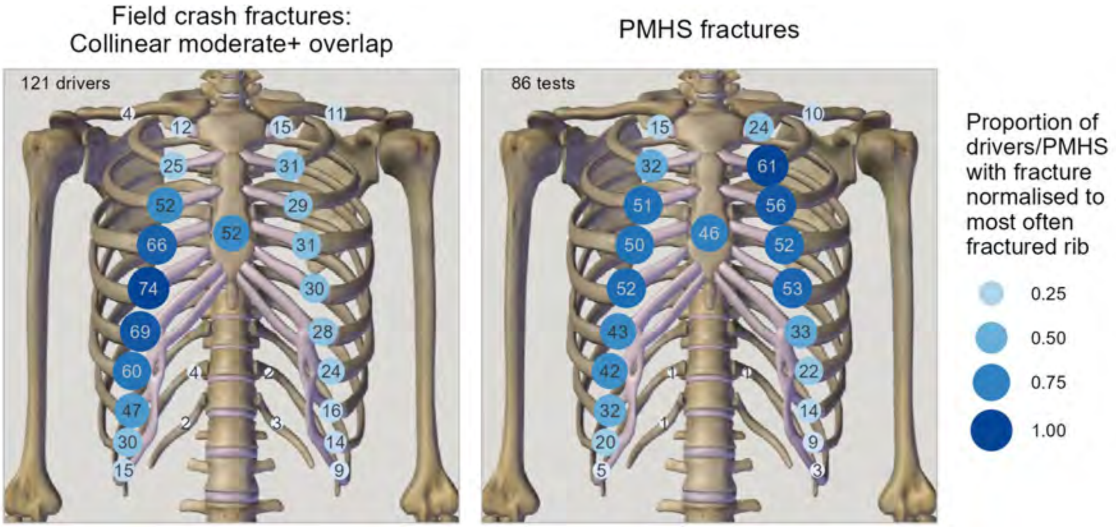

Fig. 4. Fractured ribs in field crashes and PMHS sled tests.

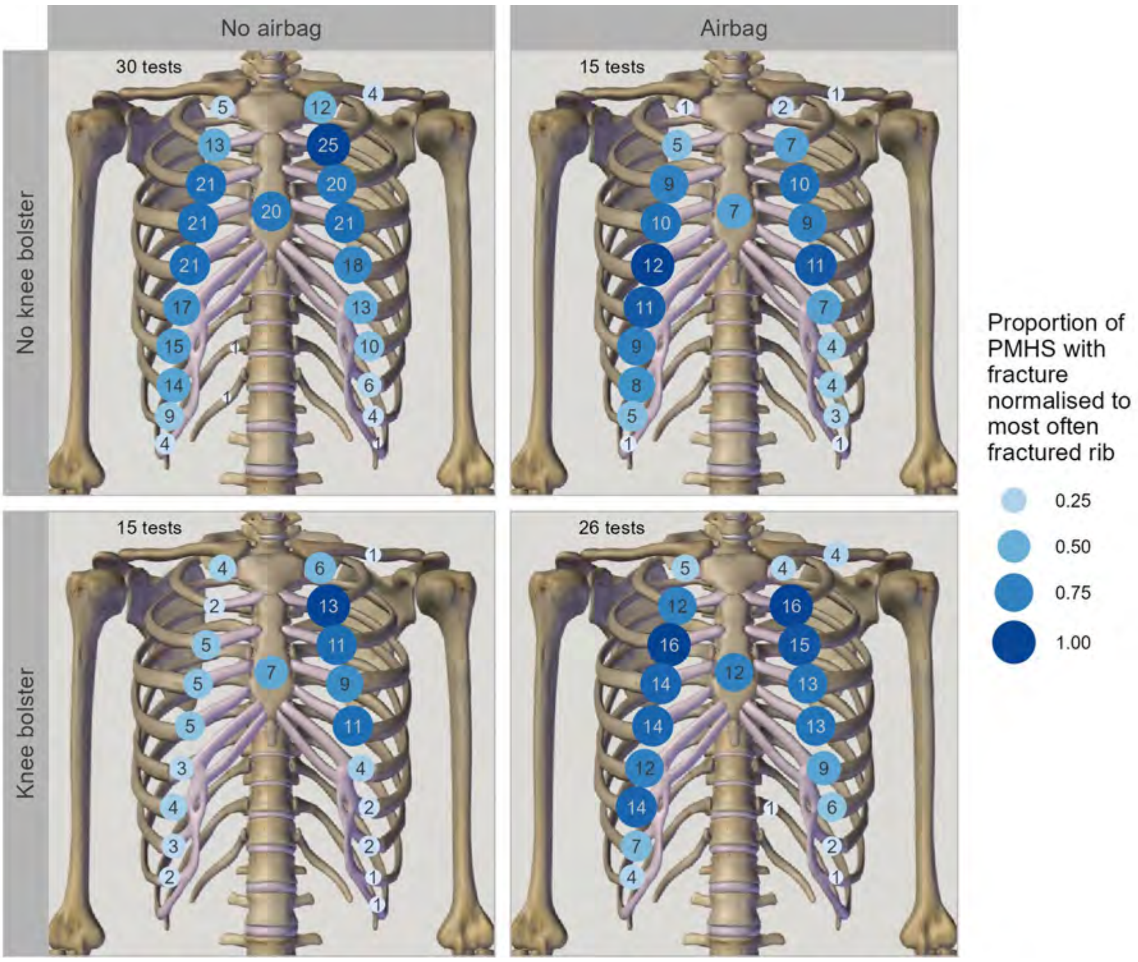

Fig. 5. Fractured ribs in PMHS tests by airbag and knee bolster presence.

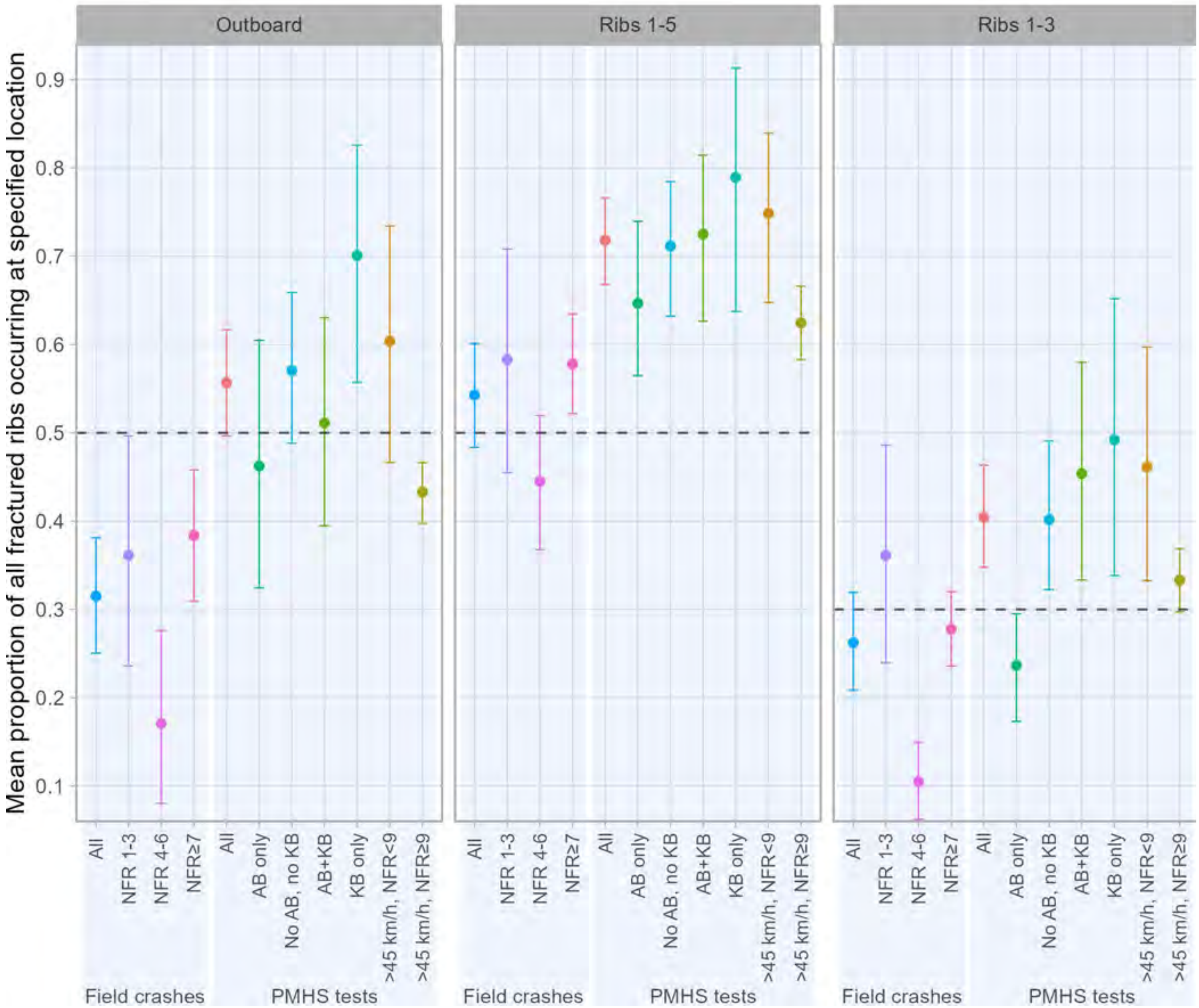

Fig. 6. Mean bootstrap proportions and 95% confidence intervals for fractured rib locations in collinear moderate+ overlap crashes and PMHS sled tests. The four PMHS restraint conditions are listed in order of assumed torso pitch angle.

Note: AB = airbag, KB = knee bolster, NFR = number of fractured ribs.

When considering the lateral distribution of fractured ribs, a significantly lower proportion of fractures in field crashes occurred on the outboard side than in all types of PMHS tests except for the AB condition. Drivers with 4–6 fractured ribs had a significantly lower proportion of outboard fractures than drivers with NFR≤3 or NFR≥7. The highest proportion of outboard fractures occurred for PMHSs in the KB condition; this was significantly different from the proportions for the AB and AB+KB conditions. In PMHS tests with a delta-V above 45 km/h, there was a significant difference between PMHSs that sustained NFR<9 and NFR≥9, with those sustaining fewer fractured ribs having a greater proportion of outboard fractures (9 was the median NFR for PMHS tests at this severity).

The vertical distribution of fractured ribs was assessed using two different groupings: ribs 1–5 vs. 6–10 and ribs 1–3 vs. 4–10. By both measures, fractured ribs in field crashes occurred more inferiorly on the thorax than all types of PMHS tests with only one exception — a similar proportion of fractures occurred in ribs 1–3 for drivers in field crashes and PMHSs with the AB restraint. The distribution of fractures for drivers with NFR 4–6 was concentrated more inferiorly than drivers with NFR≤3 or NFR≥7. Among PMHS restraint conditions, the AB condition had a significantly lower proportion of rib 1–3 fractures than each of the other conditions; none of the other differences were statistically significant. For PMHSs tested above 45 km/h, those sustaining NFR≥9 had a

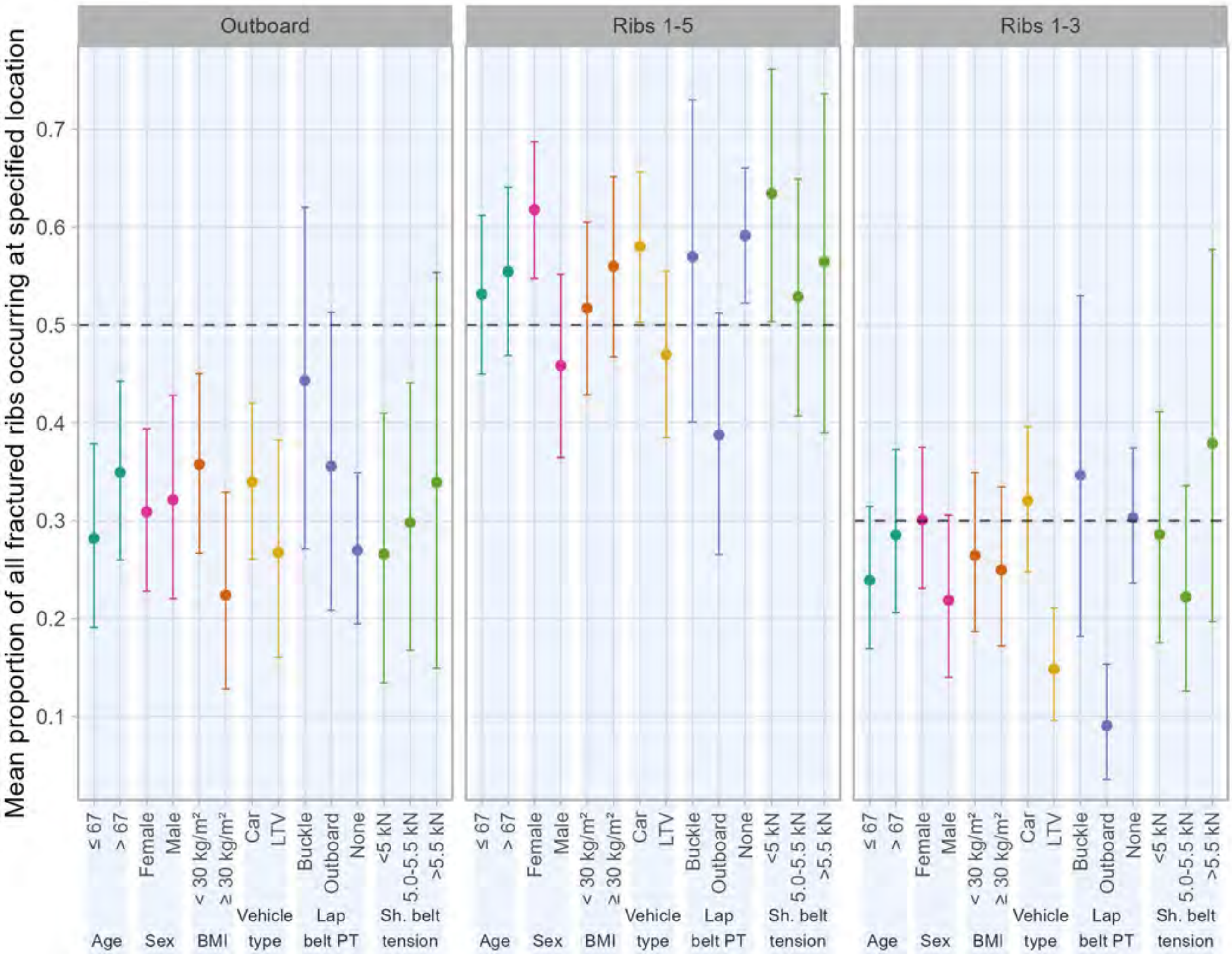

Fig. 7. Mean bootstrap proportions and 95% confidence intervals for fractured rib locations in collinear moderate+ overlap crashes by driver and vehicle characteristics. Shoulder belt tension data are from vehicle-matched US NCAP tests and only include vehicles without a lap belt pretensioner.

Note: LTV = light trucks and vans, PT = pretensioner, Sh. belt = shoulder belt.

lower proportion of fractures occurring at ribs 1–3 and 1–5 than PMHSs sustaining NFR<9; the latter was statistically significant.

Real-world factors evaluated for differences in fractured rib locations included driver age, driver sex, driver BMI, vehicle type, lap belt pretensioner type, and US NCAP shoulder belt tension. There was a correlation between lap belt pretensioner type and shoulder belt tension (Fig. 8), so only vehicles without a lap belt pretensioner were included in the analysis of belt tension. None of the factors considered was associated with a statistically significant difference in the lateral distribution of fractured ribs (Fig. 7), although BMI was close (p = 0.06). Nor did stratifying drivers into those younger and older than the median age (67) reveal any significant differences in the vertical distribution. Females did have a significantly greater proportion of fractures occurring to ribs 1–5, and a nonsignificantly greater proportion to ribs 1–3. Drivers of cars also had fractures distributed superiorly on the thorax relative to drivers of LTVs. These differences generally held when stratifying by both driver sex and vehicle type (not shown in Fig. 7; fractured ribs 1–3 as proportion of all fractured ribs: females in cars = 0.30, females in LTVs = 0.15, males in cars = 0.23, males in LTVs = 0.18). Vehicles with lap belt pretensioners located at the outboard anchor had fractures distributed lower on the thorax than those in vehicles without lap belt pretensioners or those with pretensioners at the buckle anchorage. The difference between outboard and buckle PT locations in the rib 1–5 proportion was not statistically significant, but all the other differences were. As shown in Figure 8, vehicles with outboard lap belt pretensioners tended to have the lowest US NCAP shoulder belt tension, when measurements were available.

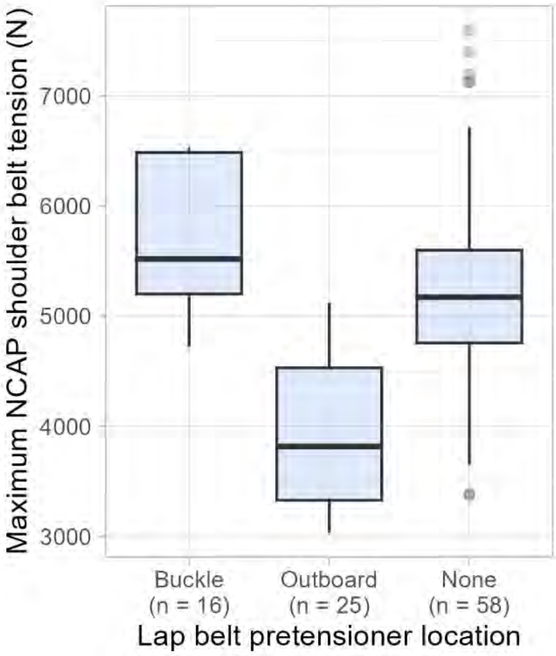

Fig. 8. NCAP shoulder belt tension by lap belt pretensioner location for vehicles involved in field crashes. There were 22 vehicles without shoulder belt tension measurements.

IV. DISCUSSION

In Phase I of this research [13], airbag and knee bolster restraints were associated with reduced risk of injury for belted PMHSs, as measured by different NFR thresholds. The benefits were generally cumulative; PMHSs restrained by both an airbag and knee bolster (AB+KB) had lower risks than those restrained by only one or the other (AB or KB), with the greatest risks for those restrained by a belt alone (noAB/KB). When considering which PMHS ribs were fractured, the current study found that patterns were most similar for the AB+KB and noAB/KB conditions (Fig. 5 and Fig. 6). Differences may be due to the effect of the restraint conditions on PMHS kinematics. Assuming the same lap and shoulder belt characteristics, the KB condition would be expected to produce the greatest torso pitch angles, and the AB condition the lowest. While torso pitch differences between the AB+KB and noAB/KB conditions likely depend on several factors, e.g., the level of belt-force limiting, and clearance to, and stiffness of, the airbag and knee bolster, it seems reasonable to assume both would fall between the KB and AB conditions, and the rib fracture patterns suggest these kinematics. PMHSs tested in the KB condition had the highest proportion of fractured ribs at the outboard and upper thorax, the AB tests produced the lowest, and the AB+KB and noAB/KB conditions were in between (Fig. 6). While rib fractures can occur away from the primary loading site due to coupling within the rib cage [14], this relationship between rib fracture patterns and expected PMHS kinematics indicates that the location of rib fractures can be a useful indicator of the most prevalent kinematics and loading patterns in field crashes as well.

The difference in PMHS rib fracture locations by restraint condition suggests real-world rib fractures are more strongly associated with excursion of the lower torso and pelvis than with forward pitch of the torso. While 70% of the ribs fractured in the PMHS KB condition were outboard, nearly 70% of ribs fractured in field crashes were inboard. Similarly, around half the ribs fractured in PMHS KB tests were ribs 1–3, but only around one-quarter of the ribs fractured in crashes were this high on the thorax. The PMHS AB tests produced rib fractures in locations more similar to field crashes. Even in this condition, however, the PMHS fractures were more evenly distributed laterally and had more fractures of ribs 1–5. This is somewhat surprising given that drivers in real-world crashes would be expected to have knee bolster engagement in many cases.

There are several possible reasons that living human drivers could have more pelvis excursion and/or less torso pitch than PMHSs in general. Pre-impact bracing and tensing are two examples. In low-speed 5-g belted sled tests, [15] reported braced volunteers had less forward excursion than PMHSs at most measured locations, but differences were greatest at the upper body regions (head centre of gravity, cervical spine, and both shoulders) and decreased or even reversed at lower body regions (hip and knee). While limited, volunteer data in higher speed tests indicate similar trends. Reference [16] reported PMHS shoulder excursions are around 50% greater than living humans with tensed muscles but no steering wheel bracing at 48 km/h. Reference [17] compared previously unpublished imagery from 48-km/h tests conducted earlier [18] in which volunteers braced against a toepan and steering wheel and were restrained by a belt and airbag. They observed the bracing posture moved the volunteer's shoulders back against the seat and the torso rotation was less than that for the PMHS. Finally, reference [19] analysed a combination of simulator and naturalistic video data and found common precrash actions included withdrawal of the head towards the head restraint and bracing against the steering wheel. Together, these studies support the hypothesis that bracing and tensing reduce torso pitch and help explain the different rib fracture distributions for living drivers and PMHSs.

Differences in lap belt engagement represent another possible reason that driver pelvis excursion could exceed PMHS values. Reference [20] found that driver BMI was the most important factor in determining lap belt fit, with both the longitudinal and vertical offset between the belt and bony pelvis increasing with BMI. In this study, the median BMI for crash-involved drivers was much higher than for PMHSs (Table I). Furthermore, drivers with BMI ≥ 30 kg/m² had more outboard rib fractures than those with lower BMI (Fig. 7), a difference that was close to being statistically significant ($p = 0.06$). The vertical distribution of fractures was similar between BMI groups, however, so BMI differences do not appear sufficient to fully explain the discrepancy between PMHS tests and field crashes. Another study found low overlap between the lap belt and bony pelvis can occur even for volunteers with lower BMI [21]. Naturalistic studies may provide meaningful insight into the possibility of belt fit differences that cannot be detected with volunteer studies in a laboratory environment.

Driver foot and leg placement could also be a factor reducing knee bolster engagement in field crashes. A recent study of frontal crashes with event data recorder output found that 70% of drivers engaged in pre-impact braking [22]. Studies of how emergency braking affects lower extremity posture have produced mixed results [23–24]. If increased knee or hip extension angles are common braking postures, they may reduce knee-thigh-hip loading from the knee bolster. To what extent the loss of this load path may be offset by bracing loads transmitted through the tibia is unknown.

Other researchers have documented thoracic injury risks associated with pelvis excursion. There are multiple contributing factors: forward movement of the pelvis and lower torso increases the overall tension in the lower portion of the shoulder belt; it increases the proportion of the tension load that is directed longitudinally [25]; and it focuses more of the overall restraint load on the weakest ribs. References [21],[26] have shown that moving the junction of the lap and shoulder belt forward produces lower levels of ATD chest compression. Reference [27] noted that injury patterns for obese occupants and PMHSs are consistent with more pelvis excursion and less torso rotation. Reference [28] measured the increased bone strength and coupling of the upper ribs relative to the lower ribs, with results emphasising the "*importance of directing belt and other restraint forces through the stiffer rib 1 and away from the more compliant lower ribs.*"

The PMHS fracture pattern in the restraint condition with the lowest injury risk (AB+KB) was similar to the pattern from the highest-risk condition (noAB/KB) [13], highlighting the fact that fracture locations alone cannot be used to assess the overall benefits of a countermeasure. The fractures that occurred in the AB+KB condition generally were the result of higher speed tests [13]. When limiting the PMHS comparisons to tests above 45 km/h (Fig. 6), less severe outcomes were associated with fracture locations more outboard and superior on the thorax. All else being equal, as NFR increases, the proportion of ribs that are fractured in each vertical and lateral group will necessarily move towards the absolute proportion defined by the grouping itself (shown by the dashed lines in Fig. 6 and Fig. 7). For example, if all 20 ribs were fractured in a test, the proportion of fractured ribs on the outboard side of the thorax must be 0.5. For this reason, the observed difference in outboard PMHS fracture proportions in tests above 45 km/h is more notable than the differences in vertical groups; the lower proportion of outboard fractures in tests producing NFR≥9 cannot be explained as the necessary result of more fractured ribs, suggesting a different loading pattern may have contributed to the higher NFR for these PMHSs.

The field crash data demonstrate even greater differences when grouping drivers by the total number of fractured ribs (Fig. 3 and Fig. 6). While the lateral and longitudinal distributions of fractured ribs for drivers with NFR≥7 were closer to the absolute rib proportions, there were significant differences between the 48 drivers with 1–3 fractured ribs and the 34 drivers with 4–6 fractured ribs. Perhaps most striking was the lack of upper outboard rib fractures for drivers with 4–6 fractured ribs; outboard ribs 1, 2, and 3 accounted for only three of the 171 total fractured ribs for this group of drivers, but 16 of 113 fractured ribs for drivers with NFR≤3. This provides further evidence that real-world thoracic injury risk could be reduced by countermeasures that are able to focus more restraint load on the superior outboard ribs and less on the inferior inboard.

Beyond the differences associated with BMI discussed above, there were other variations in the distribution of field-crash fractures that may be associated with injury risk factors (Fig. 7). Females had a greater proportion of fractures of ribs 1–5 than males. Data were insufficient to determine whether this could be explained by the stature differences between female and male drivers or whether body shape [29] or some other factor contributed. LTV drivers had lower proportions of rib 1–5 fractures ($p = 0.06$) and rib 1–3 fractures ($p < 0.001$) than car drivers. Further analysis indicated this was not fully explained by driver sex, BMI, lap belt pretensioner, and NFR differences between cars and LTVs. Additional research is needed to understand why the distribution of fractured ribs may differ by vehicle type. Possibilities include geometry of the belt, airbag, knee bolster, or seat, as well as vehicle crash dynamics, e.g., pitch [30]. Finally, while there is some indication that belt technology can affect the distribution of fractured ribs, the limited data and correlation between lap belt pretensioner type and shoulder belt tension (Fig. 8) make it impossible to draw strong conclusions. For example, drivers of vehicles with pretensioners in the outboard lap belt anchor had a significantly lower proportion of rib 1–3 fractures than drivers of vehicles without a lap belt pretensioner or with a pretensioner in the buckle, but these vehicles also tended to have lower levels of shoulder belt tension in US NCAP testing. At a minimum, this does show that the greater distribution of inferior rib fractures, a possible indicator of nonideal restraint loading, is still a problem in the newest vehicles — these tend to have low US NCAP shoulder belt tension and often are equipped with anchor-mounted pretensioners.

Field crash conditions unlikely to be represented by pure frontal sled tests were not included in comparisons with PMHS results. However, small overlap and oblique crashes are common sources of injury; over one-third of the cases that met all other inclusion criteria for this study were small overlap and/or oblique. The patterns of rib fracture in these crashes were unique (Fig. 1 and Fig. 2), indicating other injury mechanisms that must be addressed with alternative countermeasures. This is consistent with previous research [9–10] and unsurprising given the reduced benefit that would be expected from airbag and knee bolster loading, and the possibility of thoracic loading from other interior vehicle components. Many of the vehicles in this study were manufactured before the IIHS small overlap test was introduced, so some improvements already may have been made. However, it is questionable whether far-side small overlap and oblique crash injury mechanisms have been addressed. Even in near-side small overlaps, existing ATD designs may not be sensitive to the true sources of risk. For example, simulated small overlap crashes performed by [24] showed that the compliant spine of the HBM resulted in rib loading from the door trim, while the THOR ATD model did not contact the door. With more real-world data, it should be possible to explore whether deployed side torso airbags affect the distribution of fractured ribs in small overlap crashes. Addressing fractured ribs on the inboard side of the thorax may be even more difficult.

Even when considering only collinear crashes with moderate or greater overlap, the results of this study indicate a shortcoming of ATD metrics or biofidelity assessments derived from matched PMHS tests: these PMHS tests largely do not produce real-world injury outcomes. The size of the problem is likely even greater since many of the PMHS tests used for ATD assessments were not included in this study because they involved restraint conditions that do not represent the modern vehicle fleet. For example, of the 47 non-oblique PMHS sled tests used by NHTSA to establish the injury risk function for THOR maximum resultant deflection [31], 21 were excluded from this study because the peak shoulder belt tension was greater than 6 kN, the PMHS was not restrained with a shoulder belt, or the PMHS was restrained with an inflatable shoulder belt. The whole-body biofidelity assessments of THOR and Hybrid III reported by [32] were based on four PMHS test conditions, two of which were purely longitudinal. Both of these non-oblique conditions involved no airbag and a rigid knee bolster at initial contact with the PMHS knees. As shown in Figure 6, this restraint combination produced rib fracture locations most unlike the real-world. The disconnect between thoracic injury outcomes and existing ATD metrics is likely due, at least in part, to the same reasons rib fracture locations in the real-world differ from those in existing PMHS tests. While this represents a gap in current knowledge, it also suggests a potential path towards improved outcomes. If the main reasons for the discrepancy between PMHS tests and field crashes could be identified more definitively (for example, using HBMs), then existing ATDs, injury metrics, and countermeasures could be adjusted accordingly.

Limitations

As a comparison of rib fracture locations, the methodology of this study is limited by the lack of information on uninjured drivers. Uninjured PMHSs were included in Phase I of the research [13], allowing outcomes to be assessed in terms of both injury severity and injury location. Since NASS-CDS and CISS are weighted crash samples, there is no similarly straightforward process of including uninjured drivers. Drivers were stratified according to NFR to allow some comparison of injury location by injury severity, but the limitation remains. Additionally, real-world rib fracture identification using radiology is less complete than identification during autopsy. For PMHSs restrained with a seat belt but no airbag, reference [8] reported a difference in radiological detection as a function of rib number, with fractures of superior ribs less often identified. They found the addition of an airbag resulted in less discrepancy by rib number, as fractures occurred more often at lateral and posterior locations on the rib, which were more easily detected. While all the field crashes involved the deployment of an airbag, it is still possible that some of the differences in vertical fracture distribution were due to undetected fractures.

Restraint system differences between the PMHS tests and real-world crashes represent another limitation of this study. PMHS inclusion criteria were intended to produce a set of tests that represent modern restraint systems, but relatively few tests were conducted with production vehicle components. Among other variables, PMHS test configurations included a range of airbag designs and clearance values, knee bolster designs and clearance values, belt geometry, and belt pretensioners. Since it is unknown how the range of each of these variables represents the range of production vehicles in field crashes, it cannot be determined how much of the disparity between rib fracture distributions in sled tests and crashes would be eliminated by perfectly matched test conditions and how much would remain due to differences between PMHS and living humans. Finally, the field crashes involve vehicles with restraint system differences that could not be studied but that may affect the risk and location of rib fracture. One example is knee airbags, which could reduce pelvis excursion and allow greater torso pitch. There were too few cases with a coded knee-airbag deployment to provide a meaningful comparison, but evaluating this and other countermeasures could be possible in the future with a larger sample.

V. CONCLUSION

The distribution of ribs most often fractured in real-world frontal crashes is significantly different to the distribution of ribs fractured in PMHS sled tests. Over two-thirds of ribs fractured in field crashes are on the inboard side of the thorax, compared with less than half of ribs fractured in PMHS tests. The vertical distributions are also different, with field crashes more likely to result in fractures inferior on the thorax. Differences in PMHS patterns by restraint condition suggest the field crash fractures may be driven by pelvis excursion more than forward torso pitch. These findings have implications for ATD development, crashworthiness evaluation programmes, and restraint system design.

VI. ACKNOWLEDGEMENTS

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VII. REFERENCES

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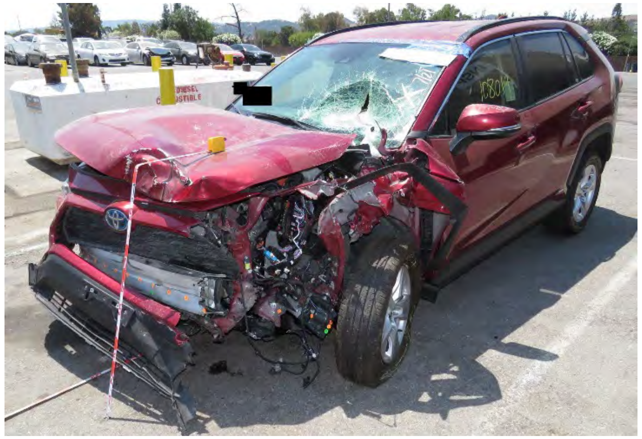
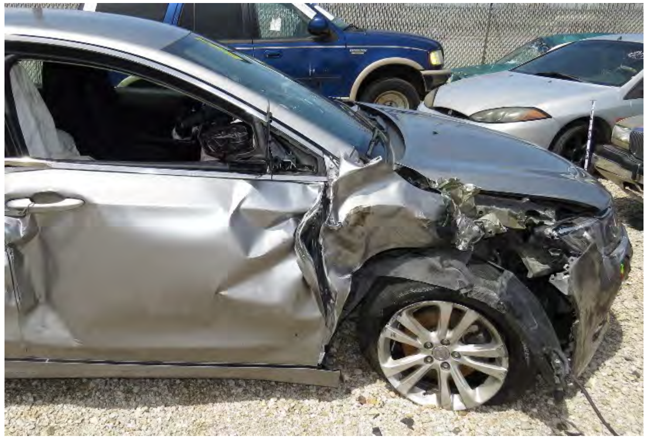
VIII. APPENDIX

TABLE A1

EXAMPLES OF THE THREE OVERLAP AND THREE OBLIQUITY CATEGORIES

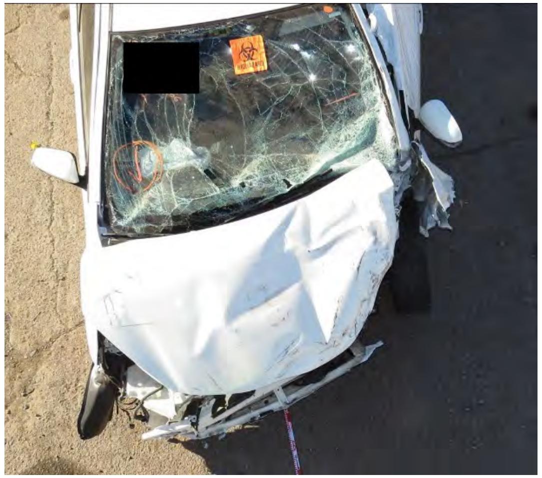


Near-side small overlap
CISS case 22698, vehicle 1



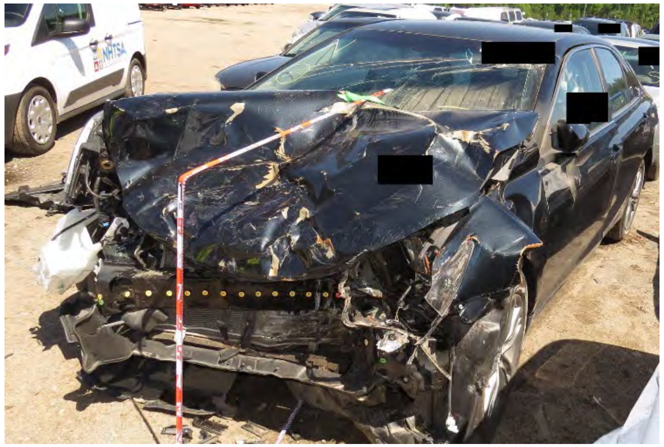
Far-side small overlap
CISS case 13798, vehicle 1

Moderate+ overlap
(moderate overlap, full overlap, centre impact)
CISS case 10024, vehicle 1



Oblique from left
CISS case 8819, vehicle 2

Oblique from right
CISS case 13567, vehicle 1



Collinear
CISS case 6809, vehicle 2

TABLE AII
PMHS TESTS INCLUDED IN REGRESSION MODELS

Test ID	Test reference[a]	Test performer	Test date	Sex	Age	Mass (kg)	Stature (cm)	Delta-V (km/h)	Airbag[b]	Knee bolster[b]	Fractured ribs
NHTSA_130	A867BL	UMTRI	1975-04-30	F	67	70	164	25	F	F	2
NHTSA_2861	RC115H	MCW	1992-06-17	F	67	57	150	48	T	F	7
NHTSA_2878	RC116C	MCW	1992-07-08	M	68	59	174	49	T	F	8
NHTSA_2879	RC122S	MCW	1992-10-28	F	81	60	157	24	F	F	4
NHTSA_2880	RC111T	MCW	1992-03-26	F	65	75	158	34	F	F	14
NHTSA_2884	RC120P	MCW	1992-09-30	M	51	66	158	24	F	F	8
NHTSA_2895	RC123G	MCW	1992-11-18	F	67	68	165	24	F	F	1
NHTSA_2963	RC128L	MCW	1993-02-19	F	67	46	154	30	T	T	3
NHTSA_2973	3P	MCW	1993-05-27	M	56	63	168	33	T	F	4
NHTSA_3254	C11	HU	1995-01-16	F	63	90	167	47	T	T	1
NHTSA_3255	C12	HU	1995-04-05	M	58	80	176	48	T	T	1
NHTSA_3270	ASTS303	UVA	1995-10-05	M	64	50	154	58	T	T	4
NHTSA_3272	ASTS305	UVA	1995-10-19	F	66	58	161	59	T	T	12
NHTSA_3336	UVA333	UVA	1996-03-27	M	50	64	170	59	T	T	6
NHTSA_3337	UVA334	UVA	1996-03-28	M	47	80	186	58	T	T	5
NHTSA_3338	UVA335	UVA	1996-04-01	M	69	66	172	59	T	T	2
NHTSA_3554	UVA412	UVA	1996-12-16	M	70	91	178	57	T	T	12
NHTSA_5230	UVA533	UVA	1999-05-27	F	67	64	163	49	T	T	1
NHTSA_5231	UVA534	UVA	1999-06-03	M	47	51	170	48	T	T	4
NHTSA_5232	UVA535	UVA	1999-06-08	F	57	53	163	48	T	T	16
NHTSA_5238	UVA544	UVA	1999-08-27	F	59	56	168	49	T	T	9
NHTSA_5239	UVA545	UVA	1999-08-31	M	67	74	176	48	T	T	3
NHTSA_8372	UVA578	UVA	1999-11-15	F	69	53	155	48	T	T	4
NHTSA_8373	UVA579	UVA	1999-11-17	F	72	59	156	48	T	T	11
NHTSA_8405	UVA668	UVA	2000-10-17	F	54	55	162	49	T	T	14
NHTSA_9546	UVA1294	UVA	2007-07-24	M	76	70	178	40	F	T	6
NHTSA_9547	UVA1295	UVA	2007-07-30	M	47	68	177	40	F	T	17
NHTSA_11491	UVAS0209	UVA	2013-10-29	F	75	36	149	30	F	T	4
NHTSA_11493	UVAS0211	UVA	2013-11-12	F	57	40	162	30	F	T	10
NHTSA_11495	UVAS0213	UVA	2013-11-21	F	65	45	152	30	F	T	5

Test ID	Test reference[a]	Test performer	Test date	Sex	Age	Mass (kg)	Stature (cm)	Delta-V (km/h)	Airbag[b]	Knee bolster[b]	Fractured ribs
NHTSA_11509	UVAS0302	UVA	2015-02-04	M	67	68	177	30	F	T	3
NHTSA_12803	UVAS0370	UVA	2016-07-29	F	72	40	154	30	F	T	2
NHTSA_12804	UVAS0371	UVA	2016-08-03	F	89	44	165	30	F	T	14
NHTSA_12806	UVAS0373	UVA	2016-08-17	F	72	56	163	30	F	T	7
NHTSA_12807	UVAS0374	UVA	2016-08-31	F	69	47	160	30	F	T	6
NHTSA_12811	UVAS0471	UVA	2017-07-18	F	60	48	154	10	F	T	2
NHTSA_12813	UVAS0473	UVA	2017-08-01	F	60	40	156	20	F	T	2
NHTSA_13109	AV2104	UMTRI	2021-01-25	M	80	80	170	33	F	F	10
NHTSA_13119	AV2106	UMTRI	2021-03-29	M	71	53	166	32	F	F	7
NHTSA_13123	NAVSC112	MCW	2021-02-25	F	78	54	166	32	F	F	13
NHTSA_13126	NAVSC115	MCW	2021-04-06	F	78	109	183	32	F	F	11
NHTSA_13156	NAVSC117	MCW	2021-07-29	F	85	35	144	32	F	F	14
NHTSA_13171	NSFSC0131	MCW	2018-10-23	F	92	48	163	48	F	F	16
NHTSA_13173	NSFSC0133	MCW	2018-11-06	F	70	46	147	48	F	F	12
NHTSA_13175	NSFSC0135	MCW	2018-11-10	F	83	37	157	48	F	F	12
NHTSA_13181	NSFSC0141	MCW	2019-03-12	F	58	38	160	48	T	T	10
NHTSA_13196	AV2211	UMTRI	2022-11-01	M	71	76	174	50	F	F	9
NHTSA_13197	NAVSC120	MCW	2021-11-03	F	52	134	171	15	F	F	1
NHTSA_13200	NAVSC123	MCW	2021-11-18	F	56	66	163	32	F	F	7
NHTSA_13209	NAVSC132	MCW	2022-06-21	F	69	109	162	50	F	F	17
NHTSA_13210	NAVSC133	MCW	2022-06-29	M	63	103	181	50	F	F	11
NHTSA_13211	NAVSC134	MCW	2022-07-13	F	76	50	160	50	F	F	17
NHTSA_13212	NAVSC135	MCW	2022-08-23	F	82	42	158	50	F	F	16
NHTSA_13213	NAVSC136	MCW	2022-09-01	F	86	42	171	50	F	F	12
Albert_KBAB_SWAB_1	[33]	VT	NA	M	80	82	187	56	T	T	1
Albert_KBAB_SWAB_2	[33]	VT	NA	M	71	73	190	56	T	T	9
Albert_KBAB_SWAB_3	[33]	VT	NA	M	78	77	170	56	T	T	6
Albert_KB_1	[33]	VT	NA	M	72	63	173	56	F	T	4
Albert_KB_2	[33]	VT	NA	M	63	70	182	56	F	T	6
Albert_KB_SWAB_1	[33]	VT	NA	M	57	59	167	56	T	T	5
Albert_KB_SWAB_2	[33]	VT	NA	M	88	80	180	56	T	T	14
Albert_KB_SWAB_3	[33]	VT	NA	M	67	68	183	56	T	T	9

Test ID	Test reference[a]	Test performer	Test date	Sex	Age	Mass (kg)	Stature (cm)	Delta-V (km/h)	Airbag[b]	Knee bolster[b]	Fractured ribs
IRIS13_Cad635	[34]	CEESAR	NA	F	56	57	161	50	F	F	19
Lopez_1969	[35]	UZ	NA	M	74	74	170	35	T	F	1
Lopez_1971	[35]	UZ	NA	M	73	62	167	35	T	F	3
NAVSC_109	[36]	MCW	NA	F	77	108	162	15	F	F	1
Petitjean_C05	[37]	CEESAR	NA	F	78	70	169	64	T	T	4
Petitjean_C22	[37]	CEESAR	NA	M	81	60	174	64	T	T	12
TOL_THO_N17	[38]	CEESAR	NA	M	68	62	167	54	T	F	9
TOL_THO_N18	[38]	CEESAR	NA	M	85	57	170	54	T	F	13
TOL_THO_N19	[38]	CEESAR	NA	M	66	80	169	54	T	F	18
TOL_THO_N20	[38]	CEESAR	NA	M	70	57	172	54	T	F	6
TOL_THO_N4	[38]	CEESAR	NA	M	82	68	166	50	T	F	16
TOL_THO_N5	[38]	CEESAR	NA	M	78	54	164	50	T	F	12
TOL_THO_N6	[38]	CEESAR	NA	M	79	60	163	50	T	F	10
TOL_THO_N7	[38]	CEESAR	NA	M	85	60	168	50	T	F	9
UVA_1360	[39]	UVA	NA	M	57	64	175	40	F	T	5
UVA_1386	[40]	UVA	NA	M	67	69	175	48	F	F	8
UVA_1387	[40]	UVA	NA	M	69	67	171	50	F	F	1
UVA_1389	[40]	UVA	NA	M	72	72	183	49	F	F	10
Vezin_FID11	[41]	INRETS	NA	M	46	63	183	49	T	F	8
Vezin_FID12	[41]	INRETS	NA	M	83	69	168	50	T	F	5
Vezin_FID14	[41]	INRETS	NA	M	78	82	180	30	F	F	2
Vezin_FID15	[41]	INRETS	NA	M	81	58	167	30	F	F	3
Vezin_H03	[42]	INRETS	NA	M	58	62	172	50	F	F	8
Vezin_H04	[42]	INRETS	NA	M	70	76	177	48	F	F	6

Note: [a] *A number surrounded by brackets (e.g., [35] indicates the test's corresponding reference number in the References section.*
[b] *For airbag and knee bolster status, T = true and F = false.*

TABLE AIII

SUMMARY METRICS FOR DRIVERS IN SMALL OVERLAP OR OBLIQUE CRASHES (N = 37)

	Unknown	Min	Max	Median
Age (years)	0	52	96	66
Stature (cm)	3	152	185	170
Mass (kg)	2	52	155	79
BMI (kg/m^2)	3	22.5	48.9	28.4
Fractured ribs	0	1	12	3

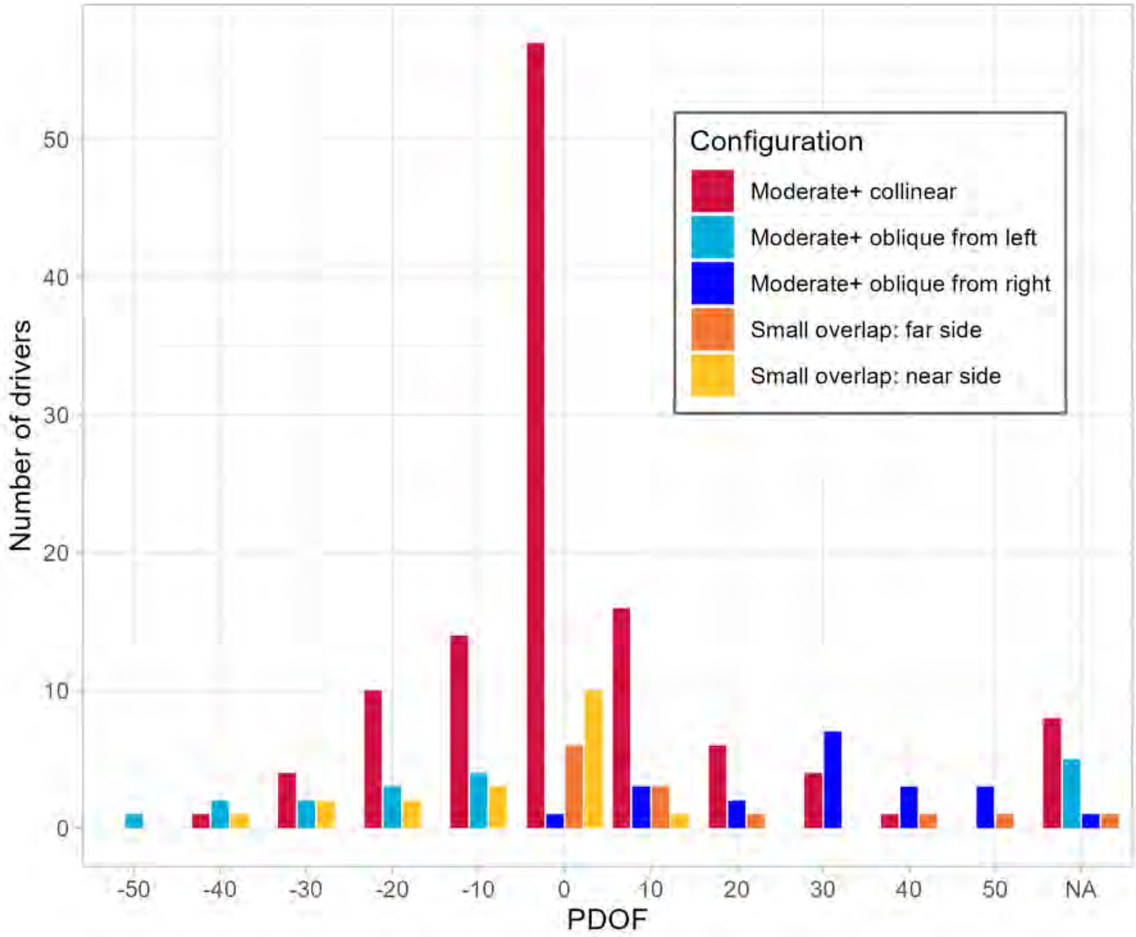


Fig A1. PDOF by crash configuration. PDOF is displayed relative to 360°.

TABLE AIV

ESTIMATED NFR PROPORTIONS THAT HAD OVERLAPPING 95% CONFIDENCE INTERVALS BUT WITH ESTIMATED DIFFERENCES THAT WERE STATISTICALLY SIGNIFICANT AT α = 0.05

NFR proportion	Group 1	Group 2	Estimated difference in proportions (Group 1–Group 2)	95% Confidence interval
		Proportions in Fig. 6		
Outboard	Field crashes: All	Field crashes: NFR 4–6	0.144	[0.021, 0.257]
Outboard	Field crashes: NFR 1–3	Field crashes: NFR 4–6	0.19	[0.025, 0.353]
Outboard	Field crashes: NFR 1–3	PMHS: No AB, no KB	−0.21	[−0.366, −0.053]
Outboard	Field crashes: NFR 1–3	PMHS: >45 km/h, NFR<9	−0.243	[−0.426, −0.051]
Outboard	PMHS: KB only	PMHS: AB+KB	0.19	[0.005, 0.365]
Outboard	PMHS: KB only	PMHS: AB only	0.238	[0.042, 0.431]
Ribs 1–5	Field crashes: All	Field crashes: NFR 4–6	0.098	[0.001, 0.195]
Ribs 1–5	Field crashes: All	PMHS: AB only	−0.104	[−0.213, −0.002]
Ribs 1–5	Field crashes: All	PMHS: >45 km/h, NFR≤9	−0.082	[−0.155, −0.01]
Ribs 1–5	Field crashes: NFR 1–3	PMHS: KB only	−0.206	[−0.388, −0.011]
Ribs 1–5	Field crashes: NFR 1–3	PMHS: >45 km/h, NFR<9	−0.166	[−0.326, −0.006]
Ribs 1–5	Field crashes: NFR≥7	PMHS: AB+KB	−0.147	[−0.254, −0.034]
Ribs 1–5	Field crashes: NFR≥7	PMHS: No AB, no KB	−0.134	[−0.225, −0.036]
Ribs 1–5	PMHS: KB only	PMHS: >45 km/h, NFR≤9	0.165	[0.007, 0.295]
Ribs 1–5	PMHS: >45 km/h, NFR≤9	PMHS: >45 km/h, NFR<9	−0.124	[−0.224, −0.016]
Ribs 1–3	Field crashes: All	PMHS: >45 km/h, NFR≤9	−0.071	[−0.136, −0.003]
Ribs 1–3	Field crashes: NFR≥7	PMHS: >45 km/h, NFR≤9	−0.056	[−0.111, 0]
Ribs 1–3	PMHS: All	PMHS: >45 km/h, NFR≤9	0.071	[0.004, 0.14]
Ribs 1–3	PMHS: KB only	PMHS: >45 km/h, NFR≤9	0.159	[0.002, 0.323]
		Proportions in Fig. 7		
Ribs 1–5	Field crashes: Females	Field crashes: Males	0.159	[0.043, 0.276]

Note: Non-overlapping confidence intervals imply statistically significant differences.
NFR = number of fractured ribs, AB = airbag, KB = knee bolster.