# Reassessing PMHS Rib Fractures in Front Sled Tests to Improve Modern Restraint Systems

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***Abstract*** Front-crash thoracic injury protection has lagged improvements in injury risk to other body regions, possibly because existing anthropometric test device injury metrics are insensitive to the predominant mechanisms and sources of real-world injury. Directly comparing injury outcomes for post-mortem human subjects (PMHSs) with outcomes for living humans may help identify injury factors that should be targeted. For this study, 113 PMHS front sled tests were identified that met inclusion criteria generally representative of the modern fleet. Logistic regression was used to model the risk of a subject sustaining at least *n* fractured ribs, with different values of *n* evaluated. Test delta-V, PMHS sex, the presence of airbag loading, and the presence of knee bolster loading were all significant predictors of the risk of sustaining the median number of fractured ribs ($n = 6$) at $\alpha = 0.05$. PMHS age did not predict the risk of ≥6 fractured ribs, but it was a significant predictor of higher numbers of fractured ribs. These tests demonstrate the protective effects of distributed airbag loading and of the lower extremity load path. The second phase of this research will compare the locations of fracture between the PMHS tests and field crashes.

***Keywords*** crashworthiness, frontal crashes, PMHS, thoracic injury

## I. INTRODUCTION

In frontal crashes, drivers restrained by a seat belt and airbag are at an elevated risk of serious thoracic injury compared with most other body regions [1]. Furthermore, unlike risks to other body regions, thoracic injury risks have not declined with improved crashworthiness evaluation scores [2]. The problem is exacerbated as driver age increases; drivers 60 or older have an estimated 50% risk of serious (Abbreviated Injury Scale [AIS] ≥3) thoracic injury in a real-world crash of a good-rated vehicle with a delta-V similar to the test [1].

Previous research indicates the disparity between crash testing and real-world thoracic injury outcomes is not simply a matter of inappropriate risk scaling, but a more fundamental problem with the ability of anthropometric test devices (ATDs) to represent the human response in real-world crashes involving modern vehicles. A study comparing responses from Hybrid III (HIII) and the Test Device for Human Occupant Restraint (THOR) ATDs with outcomes from field crashes found that HIII chest deflection was somewhat predictive of AIS2 injuries but not AIS≥3, while THOR deflections were inversely correlated with injury outcome [3]. Peak tension in the upper shoulder belt was the single test metric that best predicted field injuries. While limitations of the single-point HIII deflection measure already were well-established, the authors hypothesised that the THOR response did not adequately represent the real-world benefits of shared loading from a seat belt and airbag. Other studies have produced similar observations [4–6].

Several requirements must be met for ATD metrics in crash tests to predict human injury outcomes in field crashes. First, the response *noise* created by the range of real-world risk factors must not be so great that it overwhelms the *signal* that can be measured in a limited set of crashworthiness evaluations. Occupant age, anthropometry, precrash kinematics, crash overlap, crash pulse, and component intrusion are only some of the factors that may affect thoracic injury outcome. Second, any non-biofidelic restraint load paths resulting from the ATD design must not dominate the dummy response. Third, the specific ATD metrics chosen to measure the biofidelic portion of the response must be relatively insensitive to spurious sources of risk. For example, both HIII and THOR deflections are sensitive to belt position, which has unknown real-world importance.

There is some limited evidence that crash testing can meet the first requirement listed above, namely that a limited set of crash tests can represent the mean response from a diverse set of real-world crashes. Overall front crash test ratings have been shown to correlate to the risk of fatality [7–9] and injury for several body regions [2].

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Furthermore, even within the best-rated vehicles, specific measurements recorded by HIII for the lower extremities predict injury for female drivers [10]. Furthermore, as previously mentioned, peak shoulder belt loads recorded in crash tests are related to thoracic injury outcomes [3]. While none of these observations conclusively demonstrate meaningful real-world thoracic injury predictions are possible with the right ATD measurement, they do indicate the potential for such a measurement to be identified, if it exists.

One possible means of identifying the sources of real-world thoracic injury to which ATD metrics must be sensitive is an in-depth comparison of post-mortem human subject (PMHS) sled tests with field crash data. ATDs are intended to link the knowledge of human injury tolerance obtained from PMHS testing with the vehicle crash environment. Currently, this is done almost exclusively using the relationship between PMHS and ATD deflection measured at one or more locations on the thorax. However, deflection is itself a surrogate for injury and the process of linking PMHS and ATD deflection introduces additional potential sources of inaccuracy in the resulting injury risk prediction. Temporarily removing the intermediate ATD crash tests from the analysis of field crash data may enable a better understanding of what risk factors are most important. Rib fracture data provide one means of comparison. Since PMHS sled tests have known restraint conditions and loading inputs, resulting patterns of rib fracture locations could indicate likely injury sources for living humans with similar patterns. If successful, this information could then be used to improve crash tests and ATD metrics to be more sensitive to the predominant injury sources.

Given the wide range of conditions that have been used for sled tests, simply comparing all PMHS and field rib-fracture data would be inappropriate. Many restraint conditions included in the literature are not representative of production restraint systems that exist in today's fleet, such as blunt hub loading, inflatable belts, two-point belts, or shoulder belts with unlimited loads. Inclusion criteria should focus on selecting test conditions that capture real-world loading possibilities in modern vehicles.

After selecting appropriate criteria for PMHS sled tests, there were two necessary components for this analysis. First, factors that contribute to the overall PMHS injury severity must be identified. Second, the patterns of fractured ribs in PMHS tests and field crashes can be compared. Without the first step, it would be impossible to identify whether a restraint system difference is associated with a different injury risk or just a difference in the location of the fractured ribs. For example, a restraint system that includes more airbag loading could result in different fracture locations than a belt-dominated system without reducing the total number of fractured ribs. The two phases require somewhat different datasets, and involve separate methods, outcome variables, and applications. These are outlined in Table I. Given these differences, the two phases have been conducted as distinct analyses to preserve clarity. This study contains Phase I while Phase II is presented in a second paper [11].

TABLE I
RELATING PMHS RIB FRACTURES TO REAL-WORLD INJURY

| | Phase I | Phase II |
|---|---|---|
| *Goal* | Identify restraint and occupant factors in PMHS sled tests that affect injury severity | Use comparison of PMHS and real-world rib fracture locations to identify real-world loading conditions |
| *PMHS sled tests* | Tests with a known number of fractured ribs, including 0; location of fractures not required | Tests with 1 or more fractured ribs, all with known location |
| *Field crash data* | Injury risk estimates from previous studies | Crashes with 1 or more fractured ribs, all with known location |
| *Outcome variable* | Total number of fractured ribs | Location of fractured ribs |
| *Analysis method* | Logistic regression models of whether total number of fractured ribs exceeds a certain threshold | Graphical and quantitative comparison of fracture locations for PMHSs and field crashes; on the individual rib level and proportions for certain groups of ribs |

## II. METHODS

PMHS sled tests were identified from the literature and the biomechanics test database maintained by the National Highway Traffic Safety Administration (NHTSA). Inclusion criteria were selected to ensure the resulting test conditions were relevant to modern vehicle restraint systems and would be compatible with the real-world comparisons performed in Phase II. The inclusion criteria were: pure frontal sled pulse (non-oblique); three-point belt restraint with peak shoulder belt tension < 6 kN; no contact between the 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; and no PMHS fractures attributed to instrumentation. Tests with and without airbags and knee bolsters were included. While all production vehicle driver-restraint systems have airbags and knee bolsters, one goal of this study was to determine the extent to which these features affect thoracic injury outcome, since the degree to which they provide load paths in field crashes likely varies by vehicle model and occupant characteristics. In addition, including tests without knee bolsters and airbags allows the results to inform efforts to improve rear-seat thoracic protection [12–13].

Logistic regression was used to model the likelihood of a PMHS sustaining $n$ or more fractured ribs, with different values for $n$. The primary models used the median number of fractured ribs (NFR) for $n$, since this generally provides the most statistical power for detecting significant effects. However, models were fit for a range of values for $n$ to investigate whether effects for different covariates were sensitive to the specific threshold. In addition, a model estimating the risk of a PMHS sustaining NFR≥9 was compared with the AIS≥3 risk curve calculated in [1] for drivers ages 60 or older. A threshold of nine fractured ribs was selected based on reports [14] that this number detected in autopsy best represents the AIS3 level that would be clinically detected in living humans. This also generally aligns with [15], who found that radiologists detected 24% of fractures identified at autopsy when the PMHS was subjected to combined belt and airbag loading, and 44% when the PMHS was tested with a belt but no airbag. These findings imply that three fractured ribs (AIS3) identified on an X-ray indicate approximately 6–12 fractured ribs would be identified through autopsy, although the authors cautioned that the wide range of undiagnosed PMHS fractures meant that a single adjustment would not capture the actual AIS for many individuals [15].

Covariates evaluated in the logistic regression models included specifics of the test (sled delta-V and peak deceleration), PMHS details (age, sex, stature, mass, and body mass index [BMI]), and restraint system (peak shoulder belt tension, presence of an airbag, and presence of a knee bolster). Given the range of airbag and knee bolster characteristics included in PMHS tests, these restraint technologies were reduced to binary variables indicating that they were present and served as a load path in the test. Tests with knee bolsters that were not contacted by the PMHS were treated as tests without knee bolsters. Statistical significance was assessed at the $\alpha = 0.05$ level. Variables exhibiting high collinearity, e.g., PMHS stature, mass, and BMI, were evaluated in separate models prior to selecting a single metric, if any, that had the greatest effect on the NFR. When multiple variables had estimated effects that were statistically significant, model fit was assessed using the area under the receiver-operating characteristic curve (AUC).

Several PMHS test series have focused on evaluating thoracic injury for small females. Since small female anthropometry represents a minority of the exposed real-world population, their potential overrepresentation in the PMHS dataset could lead to findings that cannot be generalised. To evaluate this possibility, the primary regression model was fit to all available PMHS data and also to PMHSs with a mass of at least 55 kg.

Since peak shoulder belt tension has been shown to predict thoracic injury risk in field crashes [3], PMHS data also were used to investigate the relationship between belt tension and test severity, occupant mass, and the presence of an airbag or knee bolster. Linear regression models of the peak shoulder belt tension were specified using these covariates. Since peak belt tension is related to the force limiter threshold, if any, published force limiter thresholds were also considered.

## III. RESULTS

There were 113 PMHS tests that met the inclusion criteria. These are listed in Table AI in the Appendix. Roughly one-third of the tests were conducted without a knee bolster or airbag, one-quarter with both, one-quarter with a knee bolster but no airbag, and one-sixth with an airbag but no knee bolster. More of the PMHSs were male (57%) than female. Other summary metrics are shown in Table II, and by restraint condition in Table AII. Figure 1 shows the NFR by delta-V, airbag and knee bolster presence, PMHS sex, and PMHS age.

TABLE II
PMHS TEST SUMMARY METRICS

| | Min | Max | Median | Mean | SD |
|---|---|---|---|---|---|
| *Delta-V (km/h)* | 9 | 64 | 47 | 40 | 14 |
| *Peak sled deceleration (g)* | 4 | 47 | 16 | 19 | 11 |
| *PMHS age (years)* | 39 | 92 | 67 | 67 | 12 |
| *PMHS stature (cm)* | 144 | 191 | 168 | 169 | 10 |
| *PMHS mass (kg)* | 28 | 134 | 64 | 65 | 18 |
| *PMHS BMI (kg/m$^2$)* | 12 | 46 | 22 | 23 | 5 |
| *Peak shoulder belt tension (N)* | 675 | 5921 | 3694 | 3590 | 1360 |
| *Fractured ribs* | 0 | 19 | 5 | 6 | 5 |

*Note: SD = standard deviation*

The PMHS sustained a median of five fractured ribs; 52% sustained 0–5 fractured ribs. Based on this, the primary logistic regression models estimated the odds of sustaining NFR≥6. Correlation coefficients are shown in Figure 2 for all the numeric variables that were investigated. Due to their collinearity, PMHS stature, mass, and BMI were investigated in separate models, as were sled delta-V, peak sled deceleration, and shoulder belt tension (Appendix B). None of the estimated effects of the PMHS anthropometric measures were close to being statistically significant at the $\alpha = 0.05$ level while also controlling for sex. Among the correlated test measures, estimated effects for delta-V, peak sled deceleration, and shoulder belt tension all were statistically significant with $p < 0.001$, but the model with delta-V had the highest AUC so it was retained in all models.

Table III shows the estimated effects of test delta-V, PMHS sex, airbag presence, and knee bolster presence on the odds of a PMHS sustaining NFR≥6. Results are shown for all PMHSs as well as those with a mass of at least 55 kg. For both sets of tests, the risk of a PMHS sustaining NFR≥6 increased with increasing delta-V, and was greater for female PMHSs, for PMHSs restrained without an airbag, and for PMHSs restrained without a knee bolster. When combined with these metrics, none of the other covariates (peak sled deceleration, shoulder belt tension, or PMHS age, mass, stature, or BMI) had estimated effects that were statistically significant, whether modeling outcomes for all PMHSs or only for those with a mass of at least 55 kg. Additionally, none of the first-order interaction terms between delta-V, PMHS sex, airbag presence, and knee bolster presence were statistically significant.

Figure 3 shows the effect of varying the threshold for the minimum NFR used as the outcome variable in the logistic regression models. Since the effect of PMHS age was found to be a significant predictor for some threshold levels, it was included as a covariate in addition to the four variables already identified as having significant effects on the likelihood of sustaining NFR≥6 (Table III). Age was the only covariate with an estimated effect that changed direction based on the NFR threshold, but the estimated reductions in the odds of NFR≥4, NFR≥5, and NFR≥7 with increasing age were small and not statistically significant. In contrast, when using thresholds of nine or more fractured ribs for the injury response, increasing age was associated with a significant or near-significant increase in risk.

Figure 4 shows the estimated risk of NFR≥9 for a PMHS tested with an airbag and knee bolster compared with the real-world injury AIS≥3 thoracic injury risks estimated in [1]. Estimated risks for PMHSs aged 50 and 70 years were used to represent the age groups from the 2019 study because they are close to the median age values for exposed drivers in the real-world crashes (51 and 71 years old, respectively).

Most of the PMHS tests were conducted with a force-limited shoulder belt (82 of 113). The relationship between the reported force limiter threshold and the measured shoulder belt tension is shown in Figure 5. To evaluate the effects of other factors on shoulder belt load while limiting the potential for different force limiter levels to affect the results, linear regression models of belt tension were based on the 69 tests without a force limiter or where the force limit was reported as 3.5–4.5 kN. Interaction terms were evaluated between the presence of a force limiter and the other covariates; estimates for the interactions between a force limiter and delta-V and between a force limiter and PMHS mass were statistically significant at $\alpha = 0.05$ and retained in the final model. Results of this model are shown in Table IV. Regardless of force limiter status, the presence of an airbag was associated with a significant 535 N reduction in the peak shoulder belt tension, while the presence of a knee bolster was associated with a nonsignificant increase of 260 N. To illustrate the significant interaction terms, Figure 6 displays the estimated effects of delta-V and PMHS mass for belts with and without a force limiter. The estimated effect of an airbag on peak belt load is also shown.

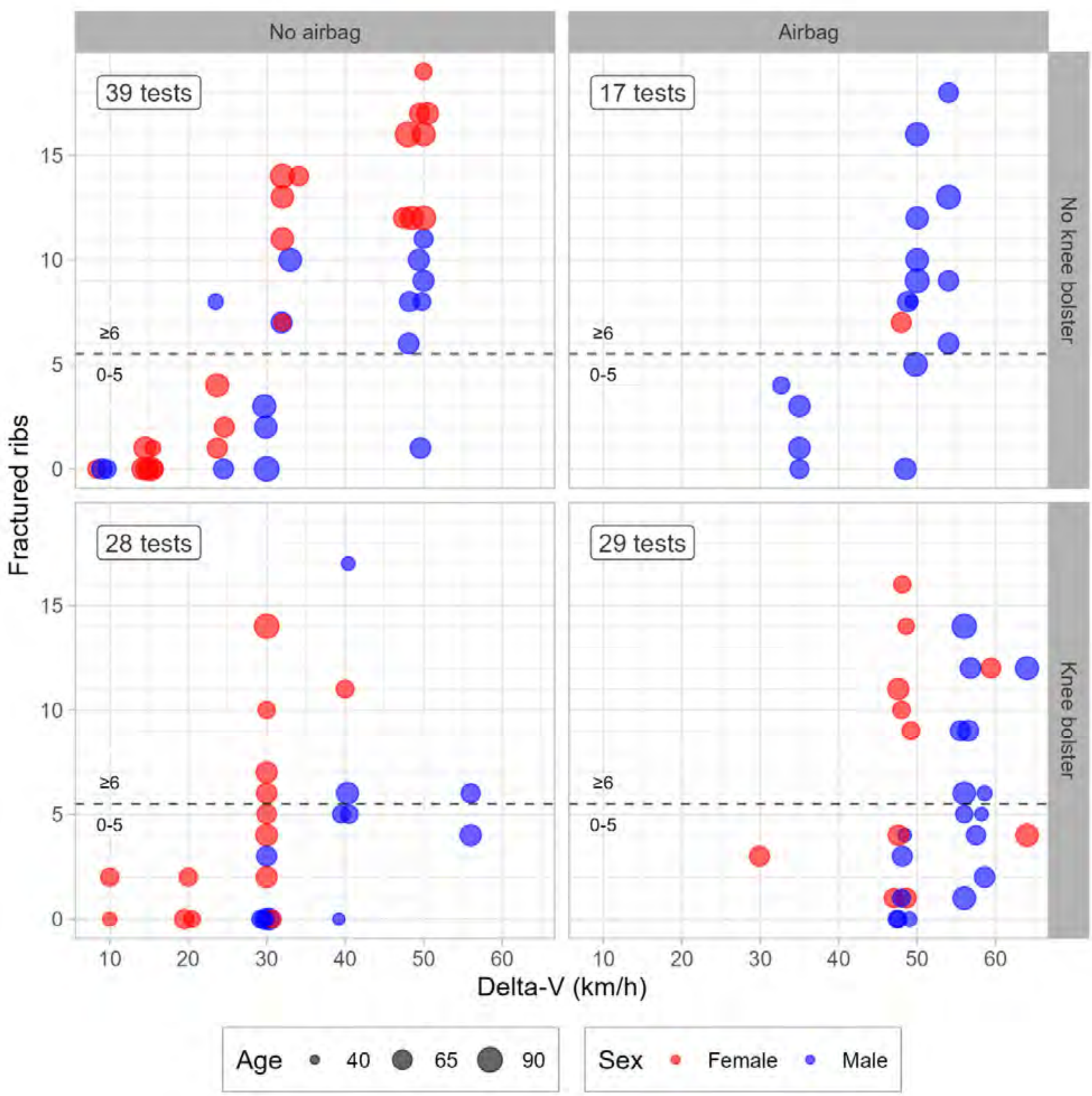


Fig. 1. Number of fractured ribs by test delta-V, airbag and knee bolster status, and PMHS age and sex.

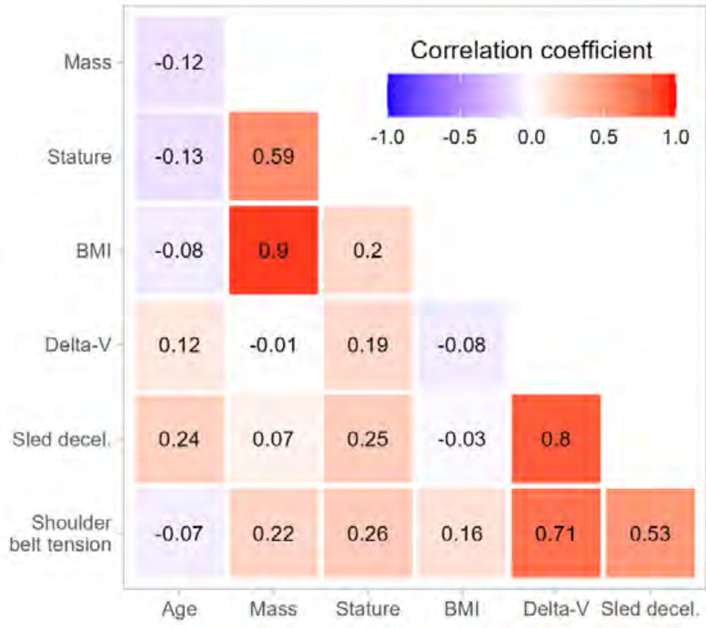


Fig. 2. Pearson correlation coefficients for PMHS test measures.

TABLE III
LOGISTIC REGRESSION MODEL RESULTS

| PMHS | Outcome | Parameter | Estimate | *p*-value | OR | 95% CI |
|---|---|---|---|---|---|---|
| *All (n = 113)* | NFR≥6 (n = 54) | Intercept | −6.639 | NA | NA | NA |
| | | Delta-V (+10 km/h) | 1.95 | <0.001 | 7.0 | [3.1, 16] |
| | | Female (vs. male) | 1.889 | 0.003 | 6.6 | [1.9, 23] |
| | | Airbag (vs. none) | −2.337 | 0.01 | 0.1 | [0.02, 0.54] |
| | | Knee bolster (vs. none) | −2.012 | <0.001 | 0.13 | [0.04, 0.42] |
| *Mass ≥ 55 kg (n = 83)* | NFR≥6 (n = 39) | Intercept | −6.299 | NA | NA | NA |
| | | Delta-V (+10 km/h) | 1.809 | <0.001 | 6.1 | [2.7, 14] |
| | | Female (vs. male) | 1.47 | 0.04 | 4.3 | [1.1, 17] |
| | | Airbag (vs. none) | −1.914 | 0.03 | 0.15 | [0.03, 0.83] |
| | | Knee bolster (vs. none) | −1.905 | 0.004 | 0.15 | [0.04, 0.54] |

*Note: OR = Odds Ratio; CI = Confidence Interval; NFR = number of fractured ribs.*

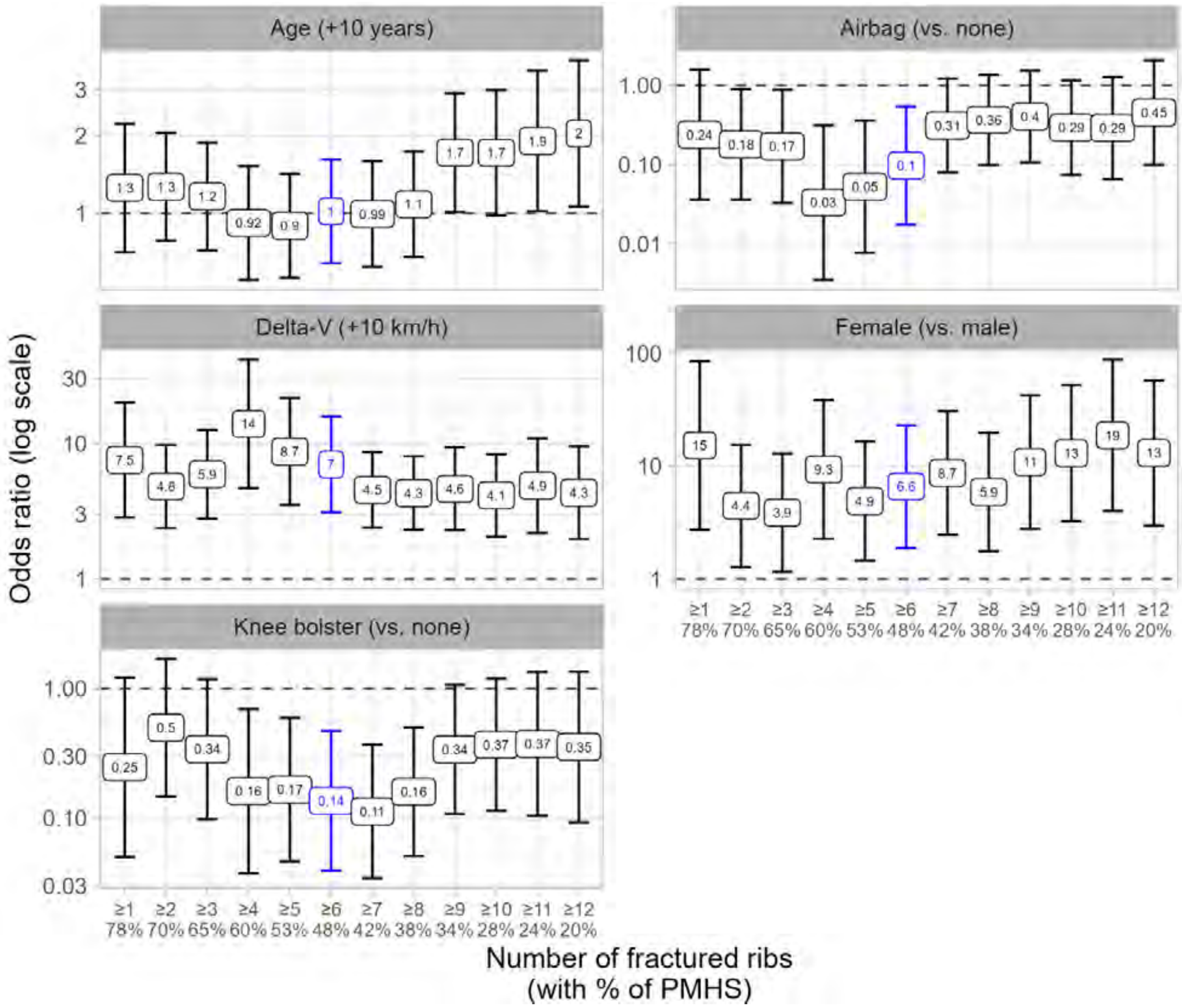


Fig. 3. Parameter odds ratios and 95% confidence intervals for PMHS sustaining different NFR. Odds of NFR≥6 appear in blue.

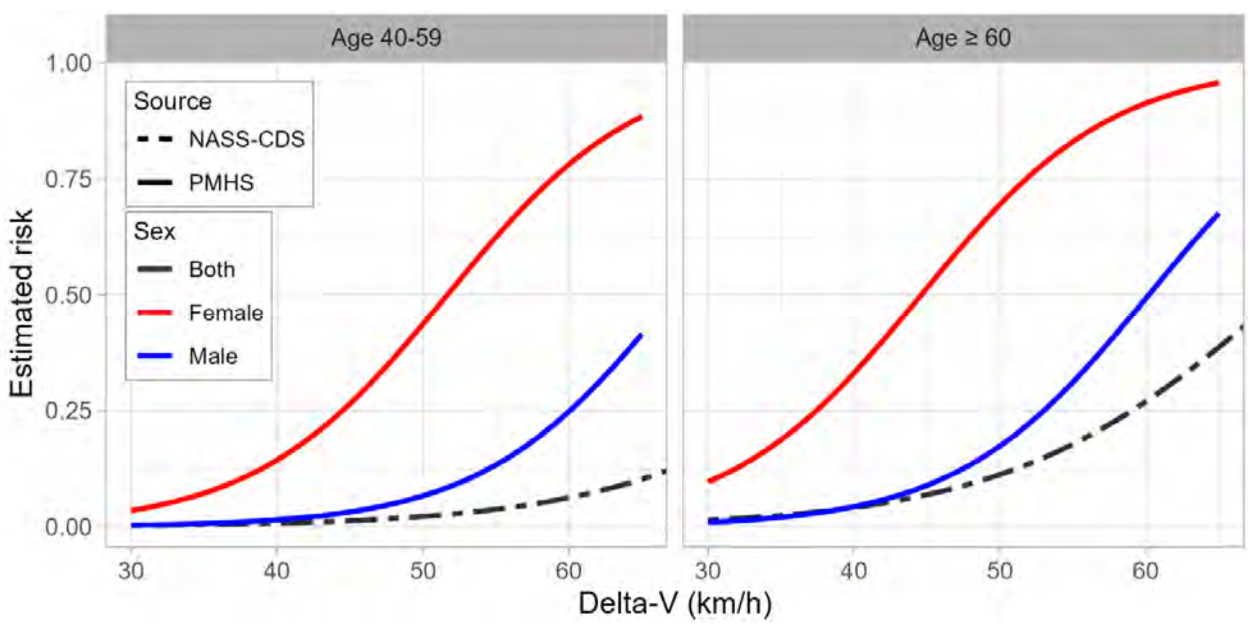


Fig. 4. Estimated risk of NFR≥9 for PMHSs tested with a knee bolster and airbag and risk of AIS≥3 thoracic injury from field crashes. PMHS estimates are limited to the range of observed delta-Vs.

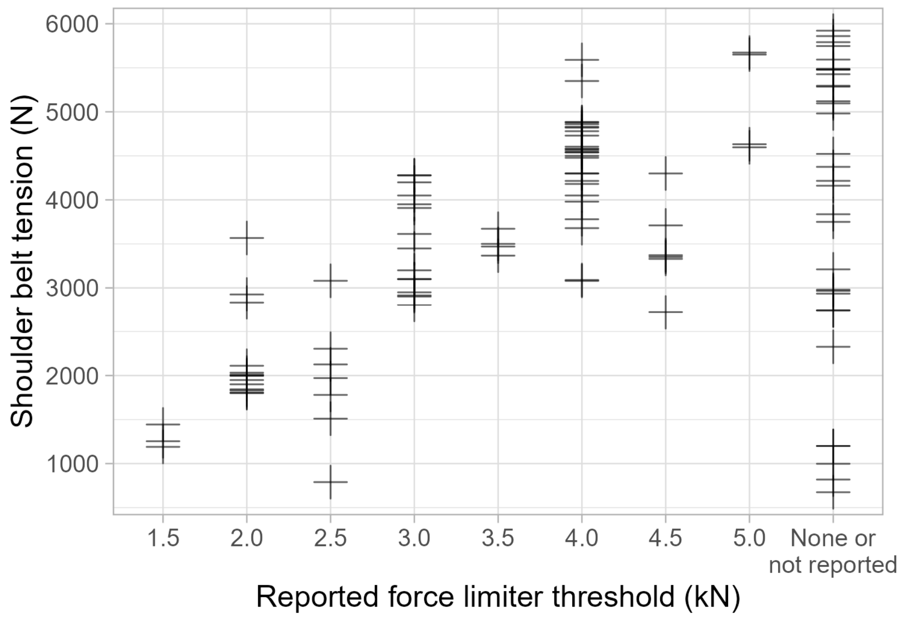


Fig. 5. Peak upper shoulder belt tension by reported force limiter threshold.

TABLE IV
RESULTS OF LINEAR REGRESSION MODEL OF PEAK SHOULDER BELT TENSION FOR PMHS TESTS WITHOUT FORCE LIMITER OR WITH 3.5 TO 4.5-KN FORCE LIMITER

| Parameter | Estimate | *p*-value |
|---|---|---|
| *Intercept* | −2949 | NA |
| *Delta-V (+1 km/h)* | 116 | <0.001 |
| *PMHS mass (+1 kg)* | 47 | <0.001 |
| *Airbag (vs. none)* | −535 | 0.01 |
| *Knee bolster (vs. none)* | 260 | 0.11 |
| *Force limiter* | 3738 | <0.001 |
| *Interaction: Delta-V with force limiter* | −69 | <0.001 |
| *Interaction: PMHS mass with force limiter* | −26 | 0.03 |

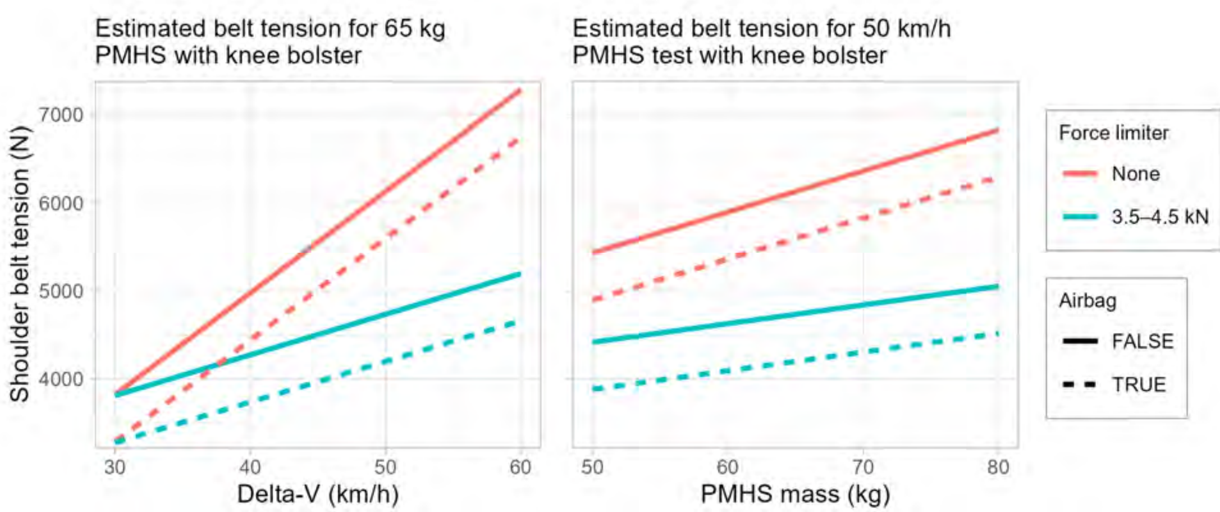


Fig. 6. Shoulder belt tension estimated by linear regression model based on test delta-V (left) and PMHS mass (right) along with force limiter and airbag status.

## IV. DISCUSSION

### *Restraint System Variables*

Hundreds of PMHS sled tests have been conducted over the past 50 years to simulate vehicle restraint system loading in front impacts. Many of these tests were used to evaluate loading conditions that are no longer relevant to the vehicle fleet. However, compiling tests that are relevant can highlight restraint strategy effects that may be obscured when focusing on individual test series, which have a necessarily limited range of input conditions. The most obvious examples from this set of 113 PMHS sled tests are the importance of thoracic load sharing with an airbag and the addition of a knee bolster load path. This is apparent in Figure 1, which shows that when tested above 35 km/h only a single test (out of 15) without an airbag or knee bolster produced five or fewer fractured ribs, in contrast with over half the tests with both an airbag and knee bolster. The lack of a significant interaction term between knee bolster and airbag presence indicates the benefits they confer are generally additive. These findings reinforce the need for ATD-based thoracic injury metrics that are sensitive to the benefits of airbags and knee bolsters.

Both HIII and THOR have limitations in their sensitivity to the different risks posed by belt and airbag loading. Reference [16] reported that the degree of risk associated with a given HIII deflection level was dependent on whether the loading was applied by a belt alone or with an airbag. References [4][17] reached a similar conclusion for THOR deflections (although both evaluated previous versions of the ATD), while the European New Car Assessment Programme (Euro NCAP) THOR test protocol explicitly notes that the injury risk data do not apply to shared airbag and belt loading [18]. The strong relationship between airbag presence and PMHS rib fracture indicates that existing ATD metrics are unlikely to encourage restraint systems that minimise real-world injury risk; novel approaches are likely required.

Ensuring an ATD can replicate the improved PMHS thoracic injury outcomes associated with the knee bolster load path is even more challenging, since it involves the entire knee-thigh-hip complex as well as the spine. The biofidelity of the pelvis under lap belt loading will also affect the degree of excursion and engagement with the knee bolster. The THOR pelvis was designed with improved geometry relative to HIII, and the compliance of the femur is more biofidelic [19]. However, the THOR femur is also longer than that of HIII, which will result in earlier knee bolster engagement when seated similarly. This effect may be magnified in the US NCAP and Euro NCAP crash test programmes where the tested seat position is based on the seat track length, often forward of where human drivers are likely to sit [20]. When positioned to have similar clearance between the knees and the knee bolster, [21–22] found that HIII knee kinematics were much closer to PMHS kinematics than THOR's. HIII also produced knee bolster loads more similar to the PMHS, while THOR more closely matched the lap belt force. Pelvis biofidelity was similar for the two ATDs. Regardless of which ATD is used, existing PMHS tests may themselves not represent typical real-world knee bolster loading. Besides seat track position, the degree of loading could be affected by foot placement, braking, bracing, and belt fit, among other factors [11]. Furthermore, 22 of the 57 PMHS tests with knee bolsters included in this study involved rigid bolsters that were initially contacting the knees.

Previous research has found that upper shoulder belt tension measured in crash tests is a better predictor of driver thoracic injury than any ATD measurement [3]. However, as discussed in the Introduction, using this as the sole measure of restraint system effectiveness is problematic. A secondary goal of this study was to evaluate the relationship between shoulder belt tension and other restraint, occupant, and test factors. The results (Table IV) demonstrate the ability of force limiters and airbags to reduce belt tension but also suggest why upper shoulder belt tension is insufficient for characterising the restraint system. Both an airbag and knee bolster were effective at reducing the number of fractured ribs but only the airbag was estimated to reduce peak belt load, while knee bolsters were associated with a nonsignificant 260-N increase in belt tension. It is likely that knee bolsters increase the forward pitch angle of the PMHS torso, which could simultaneously increase the tension in the upper shoulder belt while reducing the tension in the lower shoulder belt. Some of the PMHS tests included in this study had measurements of tension in the lower portion of the shoulder belt that could be evaluated as part of future research.

Another limitation of using belt tension as a primary measure of injury risk is illustrated by considering the results of the preliminary model that included belt tension instead of delta-V (Model 6 in Appendix B). In that model, the presence of an airbag was associated with a nonsignificant increase in the odds of 6 or more fractured ribs, in contrast with the significant reduction in risk when delta-V was used as a test severity control. As shown in Figure 6 (left side), PMHS tests with airbags produce the same shoulder belt tension as tests without airbags at lower delta-Vs. Using belt tension and airbag presence to represent loading severity creates a confounding effect with delta-V that masks the airbag benefit, at least in this set of tests conducted at different speeds with and without airbags. It is possible that belt tension measurements collected in crash tests — which are conducted at the same speed and in which an airbag always deploys — are less problematic, but restraint system differences in the degree of airbag loading at the same belt tension may still confound the results.

The model parameters included in this study are simplifications of the design options considered by restraint system engineers who have a range of airbag and belt load limiter properties to select from. The actual belt loading experienced by a human driver is complex and depends on several factors. While modern front seat belts all include a load limiter, many real-world crashes have severity and/or driver mass values below the levels needed to initiate the load limiter. Figure 6 shows several PMHS tests in which load limiters had lower peak tension than the published limiter threshold. Additionally, the actual restraint force generated by a given belt tension will depend on the belt anchor locations relative to the occupant, which change throughout the loading event. There was no attempt to control for belt geometry in the PMHS tests, and it is unknown whether this also may have contributed to the finding that delta-V was a better predictor of rib fracture than peak belt tension.

While improved prediction of driver thoracic injury is the main goal of this research, the findings also have implications for front- and rear-seated passengers. Reference [23] conducted a naturalistic study of front-seat passengers and found several common behaviours that may reduce the degree to which they would engage the knee bolster in a crash: full-rear seat positions, rearward foot positions that elevate the knees and thighs, and crossed legs. Conversely, the lack of a steering wheel allows for larger airbag designs and lower belt-force limit thresholds. Evaluating the extent to which vehicle manufacturers take advantage of these opportunities, or how the tradeoffs between seat positions affect overall rib fracture risk, was beyond the scope of this study. The situation is more obviously disadvantageous for rear-seat passengers in modern vehicles, who lack the potential benefits of both the airbag and knee bolster. The findings of this study reinforce the need to develop new countermeasures for rear-seat thorax protection [24].

***Occupant Variables***

The finding that female PMHS had higher risk of sustaining any number of fractured ribs contrasts with the results of field crash data evaluated in [1–2]. While the magnitude of the PMHS sex effect was reduced when small female tests were excluded (Table III), it remained statistically significant. Others have shown that males have higher bone strength even when accounting for body size differences [25] and that female bone mineral density (BMD) is generally lower and decreases more rapidly with age than male BMD [26]. While [27] found that measures other than BMD were better predictors of an individual rib's ability to resist fracture, several of these measures also were correlated with sex and age. In this study regression models evaluating the interaction between PMHS sex and age did not reveal significant effects. It is unknown how the bone quality of the tested PMHSs represents the population of crash-involved drivers; existing data are insufficient to determine whether the sex-based bone strength difference among crash-involved drivers is smaller, or whether some other factor explains elevated female PMHS risk and/or reduced female-driver risk relative to males.

Another difference between the PMHS-based results and assessments of real-world risk concerns the effect of age. Age is a well-established thoracic injury risk factor in field crashes, but it was not a predictor of the risk that a PMHS sustained at least the median NFR (≥6). This could partly be explained by the consequences of death being a requirement for entering the PMHS sample. Except for those suffering acute causes of death, younger PMHSs are more likely to be less healthy than their living cohorts, while those dying at or beyond the mean life expectancy are more likely to represent the general population. If some disease-related causes of death are associated with an increased likelihood of rib fracture (e.g. [28] and [29] reported inverse relationships between cholesterol levels and BMD), they could offset the overall aging effect observed in the crash-exposed population. Notwithstanding this possibility, the effect of age on PMHS injury differed when other NFR thresholds were used for the injury outcome variable (Fig. 3). Age was a significant predictor of higher numbers of fractured ribs, including nine or more, which [14] reported as the threshold that best corresponds to a clinically diagnosed AIS3 injury. In fact, there is some indication in the field data of a similar difference in the age effect by injury threshold. In a sample of real-world frontal crashes with moderate or greater overlap, age was a significant predictor of

AIS≥3 but not of AIS≥2 thoracic injury [1][3]. More research is needed before concluding that the sensitivity of the age effect to the NFR threshold in these PMHS tests reflects a real-world pattern.

Even when using nine fractured ribs as the AIS3-equivalent threshold for PMHSs, sled tests with knee bolsters and airbags still produced severe injury more commonly than would be expected from the real-world thoracic AIS≥3 injury rate for similar ages (Fig. 4). There are a few potential explanations for this discrepancy, in addition to the possibility that some causes of death may increase rib fracture risk. First, differences between PMHSs and living humans, whether in terms of kinematics [30–32], force-deflection response [33] or injury tolerance [31], may contribute. Second, the crash pulses used in the PMHS sled tests often were selected to represent a full-width rigid wall test, possibly elevating the deceleration levels beyond those typically experienced in field crashes, most of which are not full-width [1][34]. Finally, as discussed below, the restraint systems in production vehicles may provide better protection than the simplified representations often used in laboratory sled tests.

***Limitations***

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. Airbag designs included production systems from driver and passenger seat locations as well as foam proxies. Some knee bolsters consisted of rigid steel plates placed at initial contact with the PMHS knees, while others were made from crushable honeycomb designed to represent production bolsters or from foam sections with stiffnesses similar to knee airbags. The amount of pretest clearance between the PMHS knees and knee bolsters was not always documented; known values ranged from 0 to 15 cm. Seat designs also ranged from production versions to rigid benches and cable supports, while a variety of belt anchor locations and pretensioner technologies were represented. Due to all these variables, the estimated benefits for airbags and knee bolsters should be interpreted as broad indicators of preferred restraint strategies rather than precise risk reduction measurements for production restraint systems.

## V. CONCLUSIONS

PMHS tests demonstrate the ability of distributed airbag loading and the lower extremity load path to reduce rib fracture risk. The lack of apparent reductions in real-world thoracic injury risk for drivers could at least partly be due to a failure of crashworthiness evaluation tools to sufficiently emphasise the airbag and lower extremity load paths. Restraint improvements for both front- and rear-seat positions should focus on these strategies while managing potential tradeoffs in the risk of injuries to the head and lower extremities. To better understand the prevalent real-world thoracic injury factors, the second phase of this research [11] will compare the patterns of rib fracture in field crashes with those observed in these PMHS tests.

## VI. ACKNOWLEDGEMENTS

I am grateful to Dr. Philippe Vezin at the Université Gustave Eiffel, Dr. Xavier Trosseille at the Laboratory of Accidentology and Biomechanics, and Dr. Karthik Somasundaram at the Medical College of Wisconsin, all of whom provided additional information on PMHS tests included in the study, and to Dr. Jason Forman at the University of Virginia, who provided valuable feedback. All conclusions are my own.

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## APPENDIX A

TABLE AI

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) | Sled decel. (g) | Shoulder belt tension (N) | Airbag[b] | Knee bolster[b] | Fractured ribs |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *NHTSA_130* | A867BL | UMTRI | 1975-04-30 | F | 67 | 70 | 164 | 25 | NA | 3750 | F | F | 2 |
| *NHTSA_2861* | RC115H | MCW | 1992-06-17 | F | 67 | 57 | 150 | 48 | 18 | 5747 | T | F | 7 |
| *NHTSA_2878* | RC116C | MCW | 1992-07-08 | M | 68 | 59 | 174 | 49 | 22 | 5791 | T | F | 8 |
| *NHTSA_2879* | RC122S | MCW | 1992-10-28 | F | 81 | 60 | 157 | 24 | 14 | 3211 | F | F | 4 |
| *NHTSA_2880* | RC111T | MCW | 1992-03-26 | F | 65 | 75 | 158 | 34 | 16 | 5296 | F | F | 14 |
| *NHTSA_2884* | RC120P | MCW | 1992-09-30 | M | 51 | 66 | 158 | 24 | 18 | 4161 | F | F | 8 |
| *NHTSA_2890* | RC121C | MCW | 1992-10-15 | M | 67 | 66 | 183 | 24 | 15 | 2326 | F | F | 0 |
| *NHTSA_2895* | RC123G | MCW | 1992-11-18 | F | 67 | 68 | 165 | 24 | 15 | 2966 | F | F | 1 |
| *NHTSA_2963* | RC128L | MCW | 1993-02-19 | F | 67 | 46 | 154 | 30 | 18 | 2739 | T | T | 3 |
| *NHTSA_2973* | 3P | MCW | 1993-05-27 | M | 56 | 63 | 168 | 33 | 18 | 2739 | T | F | 4 |
| *NHTSA_3254* | C11 [35] | HU | 1995-01-16 | F | 63 | 90 | 167 | 47 | 14 | NA[c] | T | T | 1 |
| *NHTSA_3255* | C12 [35] | HU | 1995-04-05 | M | 58 | 80 | 176 | 48 | 14 | 4604 | T | T | 1 |
| *NHTSA_3256* | C13 [35] | HU | 1995-04-06 | M | 50 | 75 | 177 | 49 | 15 | 4577 | T | T | 0 |
| *NHTSA_3270* | ASTS303 | UVA | 1995-10-05 | M | 64 | 50 | 154 | 58 | 23 | 4981 | T | T | 4 |
| *NHTSA_3272* | ASTS305 | UVA | 1995-10-19 | F | 66 | 58 | 161 | 59 | 24 | 5286 | T | T | 12 |
| *NHTSA_3336* | UVA333 | UVA | 1996-03-27 | M | 50 | 64 | 170 | 59 | 24 | 2925 | T | T | 6 |
| *NHTSA_3337* | UVA334 | UVA | 1996-03-28 | M | 47 | 80 | 186 | 58 | 25 | 3567 | T | T | 5 |
| *NHTSA_3338* | UVA335 | UVA | 1996-04-01 | M | 69 | 66 | 172 | 59 | 25 | 2833 | T | T | 2 |
| *NHTSA_3554* | UVA412 | UVA | 1996-12-16 | M | 70 | 91 | 178 | 57 | 22 | 4199 | T | T | 12 |
| *NHTSA_5230* | UVA533 | UVA | 1999-05-27 | F | 67 | 64 | 163 | 49 | 16 | 3908 | T | T | 1 |
| *NHTSA_5231* | UVA534 | UVA | 1999-06-03 | M | 47 | 51 | 170 | 48 | 16 | 3448 | T | T | 4 |
| *NHTSA_5232* | UVA535 | UVA | 1999-06-08 | F | 57 | 53 | 163 | 48 | 16 | 4279 | T | T | 16 |
| *NHTSA_5238* | UVA544 | UVA | 1999-08-27 | F | 59 | 56 | 168 | 49 | 17 | 3613 | T | T | 9 |
| *NHTSA_5239* | UVA545 | UVA | 1999-08-31 | M | 67 | 74 | 176 | 48 | 17 | 4278 | T | T | 3 |
| *NHTSA_8371* | UVA577 | UVA | 1999-11-11 | M | 57 | 70 | 174 | 47 | 21 | 4478 | T | T | 0 |
| *NHTSA_8372* | UVA578 | UVA | 1999-11-15 | F | 69 | 53 | 155 | 48 | 21 | 4215 | T | T | 4 |

| Test ID | Test reference[a] | Test performer | Test date | Sex | Age | Mass (kg) | Stature (cm) | Delta-V (km/h) | Sled decel. (g) | Shoulder belt tension (N) | Airbag[b] | Knee bolster[b] | Fractured ribs |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *NHTSA_8373* | UVA579 | UVA | 1999-11-17 | F | 72 | 59 | 156 | 48 | 21 | 4885 | T | T | 11 |
| *NHTSA_8374* | UVA580 | UVA | 1999-11-19 | M | 57 | 57 | 177 | 48 | 21 | 4181 | T | T | 0 |
| *NHTSA_8405* | UVA668 | UVA | 2000-10-17 | F | 54 | 55 | 162 | 49 | 21 | 5478 | T | T | 14 |
| *NHTSA_9546* | UVA1294 | UVA | 2007-07-24 | M | 76 | 70 | 178 | 40 | 14 | 5921 | F | T | 6 |
| *NHTSA_9547* | UVA1295 | UVA | 2007-07-30 | M | 47 | 68 | 177 | 40 | 14 | 5593 | F | T | 17 |
| *NHTSA_11468* | UVAS028 | UVA | 2011-05-25 | M | 59 | 68 | 178 | 30 | 9 | 2915 | F | T | 0 |
| *NHTSA_11469* | UVAS029 | UVA | 2011-06-01 | M | 66 | 70 | 179 | 30 | 9 | 2803 | F | T | 0 |
| *NHTSA_11491* | UVAS0209 | UVA | 2013-10-29 | F | 75 | 36 | 149 | 30 | 9 | 1807 | F | T | 4 |
| *NHTSA_11493* | UVAS0211 | UVA | 2013-11-12 | F | 57 | 40 | 162 | 30 | 9 | 2032 | F | T | 10 |
| *NHTSA_11495* | UVAS0213 | UVA | 2013-11-21 | F | 65 | 45 | 152 | 30 | 9 | 1997 | F | T | 5 |
| *NHTSA_11509* | UVAS0302 | UVA | 2015-02-04 | M | 67 | 68 | 177 | 30 | 10 | 3101 | F | T | 3 |
| *NHTSA_11511* | UVAS0304 | UVA | 2015-02-19 | M | 74 | 70 | 183 | 30 | 9 | 2902 | F | T | 0 |
| *NHTSA_12803* | UVAS0370 | UVA | 2016-07-29 | F | 72 | 40 | 154 | 30 | 9 | 2010 | F | T | 2 |
| *NHTSA_12804* | UVAS0371 | UVA | 2016-08-03 | F | 89 | 44 | 165 | 30 | 9 | 1844 | F | T | 14 |
| *NHTSA_12805* | UVAS0372 | UVA | 2016-08-10 | F | 58 | 28 | 151 | 30 | 9 | 1831 | F | T | 0 |
| *NHTSA_12806* | UVAS0373 | UVA | 2016-08-17 | F | 72 | 56 | 163 | 30 | 9 | 2111 | F | T | 7 |
| *NHTSA_12807* | UVAS0374 | UVA | 2016-08-31 | F | 69 | 47 | 160 | 30 | 9 | 1949 | F | T | 6 |
| *NHTSA_12810* | UVAS0470 | UVA | 2017-07-12 | F | 48 | 41 | 152 | 10 | 4 | 675 | F | T | 0 |
| *NHTSA_12811* | UVAS0471 | UVA | 2017-07-18 | F | 60 | 48 | 154 | 10 | 4 | 819 | F | T | 2 |
| *NHTSA_12812* | UVAS0472 | UVA | 2017-07-26 | F | 64 | 60 | 164 | 20 | 6 | 1444 | F | T | 0 |
| *NHTSA_12813* | UVAS0473 | UVA | 2017-08-01 | F | 60 | 40 | 156 | 20 | 6 | 1190 | F | T | 2 |
| *NHTSA_12814* | UVAS0474 | UVA | 2017-08-09 | F | 54 | 41 | 159 | 20 | 6 | 1254 | F | T | 0 |
| *NHTSA_13109* | AV2104 | UMTRI | 2021-01-25 | M | 80 | 80 | 170 | 33 | 12 | 3353 | F | F | 10 |
| *NHTSA_13119* | AV2106 | UMTRI | 2021-03-29 | M | 71 | 53 | 166 | 32 | 13 | 3372 | F | F | 7 |
| *NHTSA_13122* | NAVSC111 | MCW | 2021-02-22 | F | 78 | 54 | 166 | 15 | 5 | 1510 | F | F | 0 |
| *NHTSA_13123* | NAVSC112 | MCW | 2021-02-25 | F | 78 | 54 | 166 | 32 | 10 | 3330 | F | F | 13 |
| *NHTSA_13125* | NAVSC113 | MCW | 2021-03-30 | F | 78 | 109 | 183 | 15 | 5 | 2304 | F | F | 0 |
| *NHTSA_13126* | NAVSC115 | MCW | 2021-04-06 | F | 78 | 109 | 183 | 32 | 10 | 4300 | F | F | 11 |
| *NHTSA_13155* | NAVSC116 | MCW | 2021-07-26 | F | 85 | 35 | 144 | 15 | 5 | 790 | F | F | 0 |
| *NHTSA_13156* | NAVSC117 | MCW | 2021-07-29 | F | 85 | 35 | 144 | 32 | 10 | 2720 | F | F | 14 |

| Test ID | Test reference[a] | Test performer | Test date | Sex | Age | Mass (kg) | Stature (cm) | Delta-V (km/h) | Sled decel. (g) | Shoulder belt tension (N) | Airbag[b] | Knee bolster[b] | Fractured ribs |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *NHTSA_13171* | NSFSC0131 | MCW | 2018-10-23 | F | 92 | 48 | 163 | 48 | 20 | 4216 | F | F | 16 |
| *NHTSA_13173* | NSFSC0133 | MCW | 2018-11-06 | F | 70 | 46 | 147 | 48 | NA | 5096 | F | F | 12 |
| *NHTSA_13175* | NSFSC0135 | MCW | 2018-11-10 | F | 83 | 37 | 157 | 48 | 20 | 3837 | F | F | 12 |
| *NHTSA_13181* | NSFSC0141 | MCW | 2019-03-12 | F | 58 | 38 | 160 | 48 | 20 | 2980 | T | T | 10 |
| *NHTSA_13196* | AV2211 | UMTRI | 2022-11-01 | M | 71 | 76 | 174 | 50 | 30 | 3081 | F | F | 9 |
| *NHTSA_13197* | NAVSC120 | MCW | 2021-11-03 | F | 52 | 134 | 171 | 15 | 5 | 2126 | F | F | 1 |
| *NHTSA_13199* | NAVSC122 | MCW | 2021-11-15 | F | 56 | 66 | 163 | 15 | 5 | 1780 | F | F | 0 |
| *NHTSA_13200* | NAVSC123 | MCW | 2021-11-18 | F | 56 | 66 | 163 | 32 | 10 | 3710 | F | F | 7 |
| *NHTSA_13209* | NAVSC132 | MCW | 2022-06-21 | F | 69 | 109 | 162 | 50 | 30 | 3950 | F | F | 17 |
| *NHTSA_13210* | NAVSC133 | MCW | 2022-06-29 | M | 63 | 103 | 181 | 50 | 30 | 4050 | F | F | 11 |
| *NHTSA_13211* | NAVSC134 | MCW | 2022-07-13 | F | 76 | 50 | 160 | 50 | 30 | 2950 | F | F | 17 |
| *NHTSA_13212* | NAVSC135 | MCW | 2022-08-23 | F | 82 | 42 | 158 | 50 | 30 | 3200 | F | F | 16 |
| *NHTSA_13213* | NAVSC136 | MCW | 2022-09-01 | F | 86 | 42 | 171 | 50 | 30 | 3100 | F | F | 12 |
| *Albert_KBAB_SWAB_1* | [6] | VT | NA | M | 80 | 82 | 187 | 56 | 47 | 4700 | T | T | 1 |
| *Albert_KBAB_SWAB_2* | [6] | VT | NA | M | 71 | 73 | 190 | 56 | 47 | 4700 | T | T | 9 |
| *Albert_KBAB_SWAB_3* | [6] | VT | NA | M | 78 | 77 | 170 | 56 | 47 | 4700 | T | T | 6 |
| *Albert_KB_1* | [6] | VT | NA | M | 72 | 63 | 173 | 56 | 47 | 4700 | F | T | 4 |
| *Albert_KB_2* | [6] | VT | NA | M | 63 | 70 | 182 | 56 | 47 | 4700 | F | T | 6 |
| *Albert_KB_SWAB_1* | [6] | VT | NA | M | 57 | 59 | 167 | 56 | 47 | 4700 | T | T | 5 |
| *Albert_KB_SWAB_2* | [6] | VT | NA | M | 88 | 80 | 180 | 56 | 47 | 4700 | T | T | 14 |
| *Albert_KB_SWAB_3* | [6] | VT | NA | M | 67 | 68 | 183 | 56 | 47 | 4700 | T | T | 9 |
| *IRIS13_Cad635* | [36] | CEESAR | NA | F | 56 | 57 | 161 | 50 | 18 | 5481 | F | F | 19 |
| *Lopez_1969* | [37] | UZ | NA | M | 74 | 74 | 170 | 35 | 14 | 2000 | T | F | 1 |
| *Lopez_1970* | [37] | UZ | NA | M | 63 | 67 | 174 | 35 | 14 | 1800 | T | F | 0 |
| *Lopez_1971* | [37] | UZ | NA | M | 73 | 62 | 167 | 35 | 14 | 1900 | T | F | 3 |
| *NAVSC_109* | [38] | MCW | NA | F | 77 | 108 | 162 | 15 | 5 | 1971 | F | F | 1 |
| *Petitjean_C05* | [4] | CEESAR | NA | F | 78 | 70 | 169 | 64 | 31 | 4560 | T | T | 4 |
| *Petitjean_C22* | [4] | CEESAR | NA | M | 81 | 60 | 174 | 64 | 31 | 3679 | T | T | 12 |
| *TOL_THO_N17* | [14] | CEESAR | NA | M | 68 | 62 | 167 | 54 | 25 | 5673 | T | F | 9 |
| *TOL_THO_N18* | [14] | CEESAR | NA | M | 85 | 57 | 170 | 54 | 25 | 4597 | T | F | 13 |

| Test ID | Test reference[a] | Test performer | Test date | Sex | Age | Mass (kg) | Stature (cm) | Delta-V (km/h) | Sled decel. (g) | Shoulder belt tension (N) | Airbag[b] | Knee bolster[b] | Fractured ribs |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *TOL_THO_N19* | [14] | CEESAR | NA | M | 66 | 80 | 169 | 54 | 25 | 5650 | T | F | 18 |
| *TOL_THO_N20* | [14] | CEESAR | NA | M | 70 | 57 | 172 | 54 | 25 | 4632 | T | F | 6 |
| *TOL_THO_N4* | [14] | CEESAR | NA | M | 82 | 68 | 166 | 50 | 37 | 3672 | T | F | 16 |
| *TOL_THO_N5* | [14] | CEESAR | NA | M | 78 | 54 | 164 | 50 | 37 | 3470 | T | F | 12 |
| *TOL_THO_N6* | [14] | CEESAR | NA | M | 79 | 60 | 163 | 50 | 37 | 3500 | T | F | 10 |
| *TOL_THO_N7* | [14] | CEESAR | NA | M | 85 | 60 | 168 | 50 | 37 | 3367 | T | F | 9 |
| *UVA_1094* | [39] | UVA | NA | M | 49 | 58 | 178 | 30 | 12 | 2935 | F | T | 0 |
| *UVA_1095* | [39] | UVA | NA | M | 44 | 77 | 172 | 30 | 12 | 4375 | F | T | 0 |
| *UVA_1096* | [39] | UVA | NA | M | 39 | 79 | 184 | 29 | 12 | 4522 | F | T | 0 |
| *UVA_1110* | [39] | UVA | NA | M | 44 | 77 | 172 | 39 | 17 | 5488 | F | T | 0 |
| *UVA_1360* | [40] | UVA | NA | M | 57 | 64 | 175 | 40 | 15 | 5860 | F | T | 5 |
| *UVA_1386* | [41] | UVA | NA | M | 67 | 69 | 175 | 48 | 23 | 4300 | F | F | 8 |
| *UVA_1387* | [41] | UVA | NA | M | 69 | 67 | 171 | 50 | 23 | 4300 | F | F | 1 |
| *UVA_1389* | [41] | UVA | NA | M | 72 | 72 | 183 | 49 | 23 | 4500 | F | F | 10 |
| *UVA_1397* | [42] | UVA | NA | F | 59 | 80 | 167 | 9 | 4 | 998 | F | T | 0 |
| *UVA_1398* | [42] | UVA | NA | F | 59 | 80 | 167 | 40 | 15 | 5427 | F | T | 11 |
| *UVA_1401* | [42] | UVA | NA | M | 69 | 84 | 178 | 9 | 4 | 1200 | F | T | 0 |
| *UVA_1404* | [42] | UVA | NA | M | 60 | 81 | 191 | 9 | 4 | 1200 | F | T | 0 |
| *UVA_1405* | [42] | UVA | NA | M | 60 | 81 | 191 | 40 | 15 | 5120 | F | T | 5 |
| *Vezin_FID11* | [43] | INRETS | NA | M | 46 | 63 | 183 | 49 | 23 | 3780 | T | F | 8 |
| *Vezin_FID12* | [43] | INRETS | NA | M | 83 | 69 | 168 | 50 | 23 | 4540 | T | F | 5 |
| *Vezin_FID13* | [43] | INRETS | NA | M | 74 | 67 | 168 | 48 | 22 | 3980 | T | F | 0 |
| *Vezin_FID14* | [43] | INRETS | NA | M | 78 | 82 | 180 | 30 | 14 | 4050 | F | F | 2 |
| *Vezin_FID15* | [43] | INRETS | NA | M | 81 | 58 | 167 | 30 | 14 | 3090 | F | F | 3 |
| *Vezin_FID16* | [43] | INRETS | NA | M | 90 | 45 | 177 | 30 | 15 | 3080 | F | F | 0 |
| *Vezin_H03* | [44] | INRETS | NA | M | 58 | 62 | 172 | 50 | 23 | 5590 | F | F | 8 |
| *Vezin_H04* | [44] | INRETS | NA | M | 70 | 76 | 177 | 48 | 20 | 5350 | 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.*
*[c] The peak shoulder belt tension was not reported for test NHTSA_3254, but Kallieris et al. report the same load limiter was used as in NHTSA_3255 and NHTSA_3256, so the peak tension is assumed to be below the 6 kN maximum allowed.*

TABLE AII
PMHS TEST SUMMARY METRICS BY RESTRAINT CONDITION

| Restraint Condition | Measure | Min | Max | Median | Mean | SD |
|---|---|---|---|---|---|---|
| *No airbag No knee bolster (n=39)* | *Delta-V (km/h)* | 9 | 50 | 32 | 33 | 15 |
| | *Peak sled deceleration (g)* | 4 | 30 | 15 | 16 | 9 |
| | *PMHS age (years)* | 51 | 92 | 71 | 72 | 11 |
| | *PMHS stature (cm)* | 144 | 191 | 166 | 168 | 11 |
| | *PMHS mass (kg)* | 35 | 134 | 66 | 69 | 23 |
| | *PMHS BMI (kg/m$^2$)* | 14 | 46 | 23 | 24 | 7 |
| | *Peak shoulder belt tension (N)* | 790 | 5590 | 3330 | 3323 | 1271 |
| | *Fractured ribs* | 0 | 19 | 7 | 7 | 6 |
| *Knee bolster No airbag (n=28)* | *Delta-V (km/h)* | 10 | 56 | 30 | 31 | 11 |
| | *Peak sled deceleration (g)* | 4 | 47 | 9 | 13 | 10 |
| | *PMHS age (years)* | 39 | 89 | 60 | 61 | 11 |
| | *PMHS stature (cm)* | 149 | 191 | 170 | 168 | 12 |
| | *PMHS mass (kg)* | 28 | 81 | 61 | 58 | 16 |
| | *PMHS BMI (kg/m$^2$)* | 12 | 29 | 21 | 20 | 4 |
| | *Peak shoulder belt tension (N)* | 675 | 5921 | 2853 | 3119 | 1695 |
| | *Fractured ribs* | 0 | 17 | 3 | 4 | 5 |
| *Airbag No knee bolster (n=17)* | *Delta-V (km/h)* | 33 | 54 | 50 | 47 | 7 |
| | *Peak sled deceleration (g)* | 14 | 37 | 23 | 24 | 8 |
| | *PMHS age (years)* | 46 | 85 | 73 | 72 | 10 |
| | *PMHS stature (cm)* | 150 | 183 | 168 | 168 | 7 |
| | *PMHS mass (kg)* | 54 | 80 | 62 | 64 | 7 |
| | *PMHS BMI (kg/m$^2$)* | 19 | 28 | 22 | 22 | 3 |
| | *Peak shoulder belt tension (N)* | 1800 | 5791 | 3780 | 3932 | 1339 |
| | *Fractured ribs* | 0 | 18 | 8 | 8 | 5 |
| *Airbag Knee bolster (n=29)* | *Delta-V (km/h)* | 30 | 64 | 49 | 52 | 7 |
| | *Peak sled deceleration (g)* | 14 | 47 | 21 | 26 | 12 |
| | *PMHS age (years)* | 47 | 88 | 66 | 64 | 11 |
| | *PMHS stature (cm)* | 154 | 190 | 170 | 170 | 10 |
| | *PMHS mass (kg)* | 38 | 91 | 64 | 65 | 13 |
| | *PMHS BMI (kg/m$^2$)* | 15 | 32 | 22 | 22 | 3 |
| | *Peak shoulder belt tension (N)* | 2739 | 5478 | 4379 | 4226 | 751 |
| | *Fractured ribs* | 0 | 16 | 5 | 6 | 5 |

**APPENDIX B**

TABLE BI
PRELIMINARY LOGISTIC REGRESSION MODELS USED TO EVALUATE CORRELATED PARAMETERS; ALL MODELS ESTIMATING ODDS OF ≥6 FRACTURED RIBS

| Model | AUC | AIC | Parameter | Estimate | *p*-value |
|---|---|---|---|---|---|
| *1* | 0.88 | 110.58 | Intercept | −6.5810 | NA |
| | | | Delta-V (+1 km/h) | 0.1950 | <0.001 |
| | | | Female (vs. male) | 1.8840 | 0.02 |
| | | | Stature (+1 cm) | −0.0003 | 0.99 |
| | | | Airbag (vs. none) | −2.3370 | 0.01 |
| | | | Knee bolster (vs. none) | −2.0110 | <0.001 |
| *2* | 0.88 | 109.74 | Intercept | −5.6590 | NA |
| | | | Delta-V (+1 km/h) | 0.1970 | <0.001 |
| | | | Female (vs. male) | 1.7730 | 0.01 |
| | | | Mass (+1 kg) | −0.0150 | 0.37 |
| | | | Airbag (vs. none) | −2.3650 | 0.01 |
| | | | Knee bolster (vs. none) | −2.0750 | <0.001 |
| *3* | 0.88 | 109.45 | Intercept | −5.3110 | NA |
| | | | Delta-V (+1 km/h) | 0.1975 | <0.001 |
| | | | Female (vs. male) | 1.9300 | 0.003 |
| | | | BMI (+1 kg/m$^2$) | −0.0612 | 0.3 |
| | | | Airbag (vs. none) | −2.3250 | 0.01 |
| | | | Knee bolster (vs. none) | −2.1580 | <0.001 |
| *4* | 0.89 | 105.48 | Intercept | −6.6490 | NA |
| | | | Delta-V (+1 km/h) | 0.1948 | <0.001 |
| | | | Female (vs. male) | 2.0870 | 0.002 |
| | | | Airbag (vs. none) | −2.2640 | 0.01 |
| | | | Knee bolster (vs. none) | −2.0630 | <0.001 |
| *5* | 0.81 | 128.66 | Intercept | −2.2490 | NA |
| | | | Peak sled deceleration (+1 g) | 0.1240 | <0.001 |
| | | | Female (vs. male) | 1.4480 | 0.01 |
| | | | Airbag (vs. none) | −0.3343 | 0.55 |
| | | | Knee bolster (vs. none) | −1.2160 | 0.01 |
| *6* | 0.81 | 125.7 | Intercept | −3.7480 | NA |
| | | | Shoulder belt tension (+1 kN) | 1.0200 | <0.001 |
| | | | Female (vs. male) | 1.5110 | 0.01 |
| | | | Airbag (vs. none) | 0.3344 | 0.5 |
| | | | Knee bolster (vs. none) | −1.4880 | 0.003 |

*Note: Models 1–3 were used to assess PMHS stature, mass, and BMI. Models 4–6 were used to assess delta-V, peak sled deceleration, and shoulder belt tension; these were limited to the 110 tests with reported values for all of these metrics. AUC = area under the receiver-operating characteristic curve; AIC = Akaike information criterion.*