Collision, Occupant, and Injury Characteristics in Low-to-moderate Speed Frontal Collisions – an Examination of U.S. Field Data from 2017-2022

Jason Forman, Ruyun Jin, Martin Östling, Hanna Jeppsson

Abstract This study investigating trends in injury types, restraint system activation, and occupant characteristics among those injured in low-to-moderate speed frontal collisions. NHTSA's CISS database (collection years 2017-2022) was queried for single-event, frontal-impact crashes where WinSmash-estimated ΔV was reported, focusing on belted drivers (fires, ejections, and rollovers excluded). This query returned 3,996 individual cases (representing 3.9 million weighted). Nineteen percent of the AIS2+ injury cases occurred from 0-15 km/h, 24% from 16-25 km/h, 26% from 26-40 km/h, and 30% from >40 km/h. Overall, 80% of cases of AIS2+ injury exhibited airbag activation. The injuries that occurred with the highest frequency below >40 km/h were AIS2+ brain injury (mostly concussion), upper extremity injury (mostly wrist fractures), and rib fractures. The height, weight, and BMI distributions for those injured tended to be similar to those exposed (with the exception of a slight shift in BMI for females). In the 26-40 km/h ΔV range, the average age for occupants experiencing AIS2+ injury was only somewhat greater (45.9 years old) than the average age of those exposed (38.8 years old). These findings are similar to trends observed recently with European data, providing guidance for scenarios and injuries to prioritize for low-to-moderate speed safety evaluation.

Keywords AIS2+ injuries, high-exposure low-severity frontal crashes, injury distribution.

I. INTRODUCTION

Motor vehicles have undoubtedly seen safety improvements over the years [1-2], due in part to engineering advances in vehicle structures, restraint performance, and collision avoidance technologies. This is encouraging, as it demonstrates that advances in the field (from development of new safety assessment methods to new engineering solutions) have the potential to have a real, tangible, observable impact on safety. Despite this encouraging news, however, motor vehicle crashes still result in over 39,000 fatalities, 1.6 million injuries [3], and over 3 million emergency department visits each year in the U.S. [4]. Overall, injuries from motor vehicle collisions result in annual U.S. economic costs of over $135 billion from lost productivity and medical expenses [5]. Thus, our work as a field is far from finished. We must continue to build on the momentum and expertise gained from the last 50 years of automobile safety research and development, striving to address ever more challenging safety concerns that remain.

The vast majority (e.g., 90% or more) of police-reported, frontal, tow away crashes are of low-to-moderate speed (e.g., ≤40 km/h [6-12]). Even though the per-crash injury risk in such collisions is quite low, the very high rates of exposure to such crashes has the net effect of resulting in many cases of injury. For example, a previous investigation [6] found that in the U.S., 72% of cases of Abbreviated Injury Scal AIS2+ injury in frontal collisions with belted occupants resulted from crashes of 34 km/h or less. This is not just a U.S. phenomenon, [7] with similar trends having been observed in an examination of a German In-Depth Accident Study (GIDAS) dataset from Germany, where 62% of cases of AIS2+ injury with belted drivers in frontal collisions occurred with a barrier energy equivalent speed of 34 km/h or below. This is a known trend that has been observed consistently, in large part, throughout the history of automobile safety research [10-12].

It is difficult to envision how to address such high-exposure, low-severity collisions, as the per-crash injury risk in such collisions is already quite low [12-13]. Reference [6] found that 72% of AIS2+ frontal-impact injury cases occurred at collision severities where the per-crash injury risk was only 3.7%. The question is, how can we prospectively assess injury risk, and decrease injury risk, when the existing per-crash injury risk is already very low? Reference [12] recognised this challenge, but also framed it as a positive, due to the very high rates of exposure, even a very modest decrease in injury risk (say, from 4% risk at the baseline, to 3% with a

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countermeasure) has the potential to eliminate thousands of cases of injury.

Given the very high rates of collision exposure (which result in a large number of cases of injury), there may be value in developing and implementing means to prospectively evaluate injury risk in low-to-moderate speed frontal collisions. Note that some existing frontal impact testing programmes seek to establish safety *up to* a specified crash severity (e.g., the Federal Motor Vehicle Safety Standards, FMVSS, 208 series). In theory, that means that vehicle crashworthiness performance is evaluated at all speeds up to that max speed. In practice, however, a singular set of Injury Assessment Reference Values (IARVs) is often used to judge performance in such evaluations, causing the evaluation to ultimately be driven by the vehicle's performance at the maximum test speed. As noted above, the majority of collisions resulting in injury are of low-to-moderate speed, where the per crash injury risk is very low. To drive down that risk even further, prospective safety assessment for low-to-moderate speed collisions may need to adopt different means for assessing risk, for example, targetting much more conservative thresholds for risk than would normally be used in higher speed evaluations.

Other evaluation programmes such as the European New Car Assessment Programme (Euro NCAP) have been contemplating dedicated evaluations for low-to-moderate speed collisions. Low-to-moderate speed collisions encompass a broad range of potential scenarios to investigate, however, bringing a host of questions. Within low-to-moderate speed frontal collisions, is there a particular collision severity range that should be the highest priority? Is there any commonality to the particular restraint scenario experienced by occupants that are injured? Are the injuries or injured body regions that are observed the same as those that are of concern for higher-speed collisions? Is there a particular subset of occupants that are affected the most by injuries in low-to-moderate speed collisions, and what are the potential implications for occupant modelling tools such as anthropomorphic test devices (ATDs) and human body models (HBMs)?

To begin to address some of these questions, [7-8] examined data from the GIDAS database, investigating trends in injury counts and risk, injury types, collision types, and occupant characteristics for various ranges of low-to-moderate speed frontal collisions (single event collisions with belted occupants). Confirming past observations, [8] found that over 65% of AIS2+ injury cases occurred with barrier equivalent speeds between 16 and 40 km/h. AIS2+ injury risk was 8.3% at speeds from 16-25 km/h, and 13.2% from 26-40 km/h. Eighty-one percent of the collisions with AIS2+ injury below 40 km/h were severe enough to cause deployment of the frontal airbags. The most common AIS2+ injuries in crashes from 16-40 km/h with airbag activation were injuries to the head (mostly concussion), thorax, upper extremity, and lower extremity. Examining occupant characteristics in GIDAS, [7] found that the distributions of occupant stature and weight among those injured tended to mirror the distributions of those exposed to collisions. While the age distribution for those exposed to collisions tended to be skewed towards young-to-middle age, the age distribution of those injured tended to be quite flat (with fairly even counts of injured occupants from ages 20-80 years old).

This study seeks to investigate the same questions as [7-8], using U.S. data By repeating a similar analysis on an independent dataset from a different country, we may be able to observe whether the trends observed in the past are robust, characteristic of collisions in general, or if they are in some way niche to a particular locale, market, or dataset. Our goal was to examine recent case collection years from National Highway Traffic Safety Administration's (NHTSA's) Crash Investigation Sampling System (CISS) to observe rates of exposure and injury in low-to-moderate speed frontal collisions with belted drivers, to observe types of injury that occur in those crashes, to observe the occupant characteristics and restraint characteristics among those exposed and those injured.

II. METHODS

NHTSA's CISS was queried for belted drivers in frontal, single-event crashes in collection years 2017-2022, in vehicles of model year (MY) 2002 and newer (chosen to harmonize with the GIDAS analysis of [8]). Cases were examined at the occupant level. Exclusion criteria included unbelted occupants, occupants other than drivers or location unknown, occupants less than 13 years old, multi-event crashes, fires, rollovers, and cases for which Winsmash-estimated ΔV was not reported. Frontal crashes were defined as crashes having a Principal Direction of Force, PDOF, from 300 to 359 or 0 to 60 degrees; a General Area of Damage (GAD) 1 or 2 equal to *F*; or

(GAD1=L/R and SHL1=F) or (GAD2=L/R and SHL2=F).

Distributions were plotted for the reported ΔV of exposure cases in the dataset, as well as cases that resulted in AIS2+ injury. As the CISS sampling strategy intentionally over-samples higher severity collisions, the ΔV distribution was examined both with the raw (unweighted) case data, and with the CISS case weights applied. In addition, occupant characteristics were examined by plotting the distributions of occupant age, stature, and Body Mass Index (BMI) by sex for all exposures and for those cases that resulted in AIS2+ injury (unweighted to observe occupant characteristic trends in the raw data).

To study the relationship between exposure rate, injury risk, and total injury frequency, counts of collision incidence and injury occurrence were examined for four different ranges of reported ΔV. The ΔV ranges were the same as those used by [8]: 0-15 km/h, 16-25 km/h, 26-40 km/h, and >40 km/h. The proportion of exposure cases that experienced injury were examined for several different types of injury, including AIS2+ injury and AIS3+ injury, as well as injuries grouped by the AIS body regions. In all cases, this proportion was calculated simply as the number of cases in the target exposure group (e.g., the target ΔV range) that experienced the injury type in question, divided by the number of exposure cases in that exposure category. For simplicity's sake, at times in this manuscript we will refer to this as *risk*. Note that care was taken to not count cases of multi-trauma multiple times in this calculation – the calculation refers to the proportion of cases that experienced at least one injury of the noted type (though in the risks calculated by body region, an individual case can potentially appear in multiple bins if it has injuries across multiple body regions). Injury risks by AIS level and body region were calculated for each of the target ΔV categories noted above.

In addition, to further elucidate the types and relative frequencies of injuries that occur in the various ΔV ranges, injury distributions were tabulated based on subcategories within the AIS body regions (showing the proportion of AIS2+ injury cases that contain at least one injury in each of these categories). These injury type categories were as follows (all of which were tabulated at the AIS2, AIS3, and AIS4+ levels): skull fracture; brain injury (including concussion, diffuse axonal injury, hematomas, vascular injury, and all other brain injuries); cervical spine, thoracic spine, and lumbar spine; upper extremity (based on the AIS body region category); ribcage fracture (including rib fractures and sternum fracture); thorax organ injury (including heart injury, lung injury, pneumothorax, hemothorax, and any other internal thoracic injury); abdomen (based on the AIS body region category); pelvis fractures (excluding acetabulum); hip fractures (fractures of the acetabulum or proximal femur); femur fractures (fractures of the mid-shaft or distal femur); tibia/fibula fractures (fractures of the proximal or mid-shaft tibia or fibula); ankle (fractures of the distal tibia or fibula, talus, calcaneus; or ankle ligament injury (including dislocation).

Finally, cases were examined by the types of restraint technology that were reported as present and deployed. Similar to [7], the distribution of reported ΔV for cases resulting in airbag deployment, and for cases without airbag deployment were plotted (plotting for all exposures, and for cases resulting in AIS2+ injury). As WinSmash often underestimates ΔV [9], the frequency of airbag deployment was also examined within each ΔV category to provide another point of context to gauge the actual severity of collisions within the categories (for example, tabulating the proportion of cases within the *0-15 km/h* category that had airbag deployment, despite the very low reported ΔV). In addition, the proportion of cases that experienced seatbelt pretensioner deployment in the two lowest ΔV categories were examined. The proportion of cases that experienced AIS2+ and AIS3+ chest injury with and without a seatbelt pretensioner were examined, to provide context for what magnitude of chest injury risk should be expected under loading from a typical seatbelt pretensioner.

III. RESULTS

The query resulted in 3,996 cases that met the selection criteria (Table I), representing nearly 3.9 million cases after applying the CISS case weights (Table II). From the unweighted data (Table I), 40% of the cases had a reported ΔV from 0-15 km/h. Thirty-five percent had a reported ΔV from 16-25 km/h; 18% from 26-40 km/h, and 7% >40 km/h. Among cases with AIS2+ injury, 19% had a reported ΔV from 0-15 km/h; 24% had a reported ΔV from 16-25 km/h; 26% 26-40 km/h; and 30% > 40 km/h. Forty-eight percent of AIS3+ injury cases had a reported ΔV less than or equal to 40 km/h, and 52% had a reported ΔV above 40 km/h. As noted above, unweighted CISS data is naturally biased towards higher severity collisions due to the CISS sampling strategy. As seen in Table II, after applying the case weights the proportions tend to shift further towards the lower-ΔV categories, with 96% of exposures, 78% of AIS2+ injury cases, and 70% of AIS3+ injury cases having ΔV's less than or equal to 40 km/h. Overall, 94% of the cases were vehicle-to-vehicle collisions (unweighted). This was relatively consistent across airbag deployment status and ΔV categories up to 40 km/h, with a decrease to 84% in the >40 km/h category.

The average driver ages for collision exposures and AIS2+ injury cases are also shown in Table I (unweighted) and Table II (weighted). The average age for collision exposures tended to be similar across ΔV categories, with the exception of collisions >40 km/h (which tended to have a somewhat lower driver age for the weighted data). The average age for AIS2+ injury cases ranged from 7-12 years greater than the average age of exposed drivers (weighted).

TABLE I
AGES AND PROPORTIONS OF DIFFERENT ΔV CATEGORIES AMONG ALL EXPOSURE CASES, AIS 2+, AND AIS3+ INJURY CASES
(CISS 2017-2022, MY 2002+, FRONTAL, BELTED DRIVER, SINGLE EVENT, UNWEIGHTED)

	0-15 km/h	16-25 km/h	26-40 km/h	> 40 km/h	All
Exposures	1602	1390	706	298	3996
%	40%	35%	18%	7%	100%
AIS2+	79	101	108	126	414
%	19%	24%	26%	30%	100%
AIS3+	6	21	31	64	122
%	5%	17%	25%	52%	100%
Avg. Age - Exp.	42.7	41.4	40.2	40.8	39.7
Avg. Age - AIS2+	48.6	49.9	49.6	43.3	47.6

TABLE II
AGES AND PROPORTIONS OF DIFFERENT ΔV CATEGORIES AMONG ALL EXPOSURE CASES, AIS 2+, AND AIS3+ INJURY CASES
(CISS 2017-2022, MY 2002+, FRONTAL, BELTED DRIVER, SINGLE EVENT, WEIGHTED)

	0-15 km/h	16-25 km/h	26-40 km/h	> 40 km/h	All
Exposures	1,635,903	1,535,734	543,627	140,606	3,855,870
%	42%	40%	14%	4%	100%
AIS2+	34,954	45,067	44,074	35,392	159,487
%	22%	28%	28%	22%	100%
AIS3+	3,843	10,083	7,998	9,354	31,277
%	12%	32%	26%	30%	100%
Avg. Age - Exp.	39.7	38.7	38.8	34.7	39.0
Avg. Age - AIS2+	51.6	49.3	45.9	41.7	47.2

Table III shows the proportion of exposure cases within each ΔV category that exhibited AIS2+ and AIS3+ injury, expressed as *risk*. In the cases at or below 40 km/h, the unweighted AIS2+ injury risk ranged from 4.9% (0-15 km/h) to 15.3% (26-40 km/h). This increased to 42.3% for cases above 40 km/h. The AIS3+ injury risk ranged from 0.4% to 4.4% for cases at or below 40 km/h, and was 21.5% for cases above 40 km/h. These risk values naturally decreased after applying the CISS case weights, decreasing the risk values by half to two-thirds.

TABLE III
RISK (CALCULATED AS # OF INJURY CASES / # OF EXPOSURES) FOR AIS2+ AND AIS3+ INJURIES, BY ΔV CATEGORY
(CISS 2017-2022, MY 2002+, FRONTAL, BELTED DRIVER, SINGLE EVENT, UNWEIGHTED AND WEIGHTED)

Unweighted	0-15 km/h	16-25 km/h	26-40 km/h	> 40 km/h	All
AIS2+	4.9%	7.3%	15.3%	42.3%	10.4%
AIS3+	0.4%	1.5%	4.4%	21.5%	3.1%
Weighted	0-15 km/h	16-25 km/h	26-40 km/h	> 40 km/h	All
AIS2+	2.1%	2.9%	8.1%	25.2%	4.1%
AIS3+	0.2%	0.7%	1.5%	6.7%	0.8%

Figure 1 shows the distributions (raw and cumulative) of reported ΔV values for all exposures, and for cases of AIS2+ injury. Consistent with Tables I and II, the vast majority of exposures occurred with reported ΔV's below 40 km/h. As a result, even though the per-crash injury risk is quite low, the majority of AIS2+ injury cases also occur with a ΔV below 40 km/h. Applying the case weights naturally shifts the exposure and injury ΔV distributions to the left, but the trend of dominance of relatively low-speed collisions is consistent when viewed either with or without the case weights.

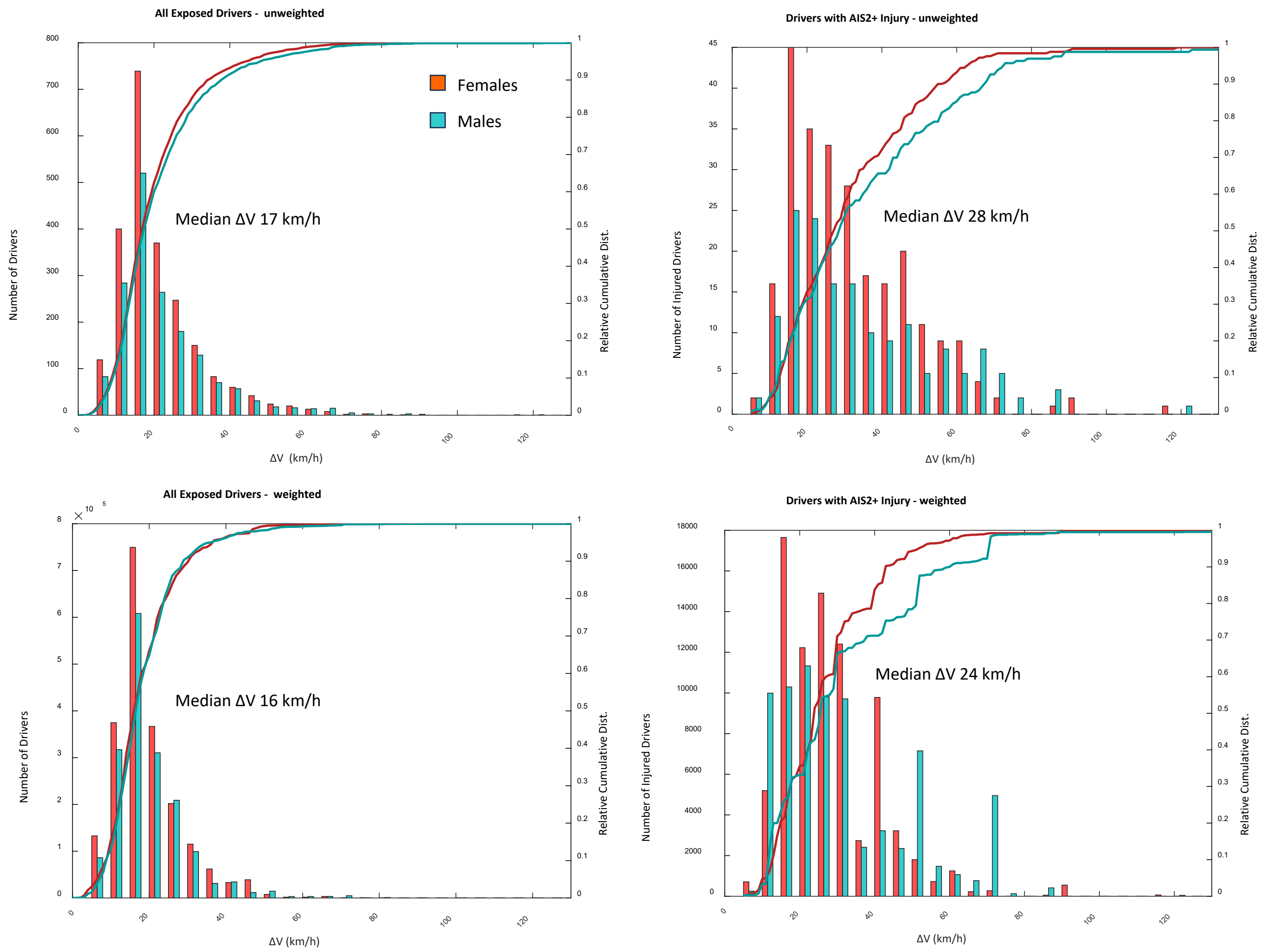

Fig. 1. Distributions of ΔVs for belted drivers in single-event frontal collisions in MY2002+ vehicles in CISS 2017-2022 (left), and distributions of ΔVs for the subset that experienced AIS2+ injury (right). Top: unweighted data. Bottom: weighted data. Coluor-coded by driver sex. Bars represent raw data and lines represent the cumulative data.

Table IV shows the proportion of exposures and injury cases that were reported to have frontal driver airbag activation, by ΔV category and injury severity. In the unweighted data, 54% of exposures and 80% of AIS2+ injury cases experienced frontal driver airbag activation. Rates of airbag activation tended to be high (above 70%) among the AIS2+ and AIS3+ injury cases in the 16-25 and 26-40 km/h ΔV ranges (with the exception of the AIS2+ injuries in the 16-25 km/h range and the AIS 3+ injuries in the 26-40 km/h range in the weighted data, which may be attributable to weighting anomalies). These trends can also be seen in Figure 2, which shows ΔV distributions (raw and cumulative) for exposures and AIS2+ injury cases with and without airbag activation. The unweighted plots in Figure 2 show that the vast majority of AIS2+ injury cases across ΔV levels exhibited driver frontal airbag activation, suggesting that even if the WinSmash-estimated ΔV was quite low, the collision was still severe enough to trigger airbag activation.

TABLE IV

PROPORTION OF CASES WITH DRIVER FRONTAL AIRBAG ACTIVATION, BY INJURY SEVERITY AND ΔV CATEGORY (CISS 2017-2022, MY 2002+, FRONTAL, BELTED DRIVER, SINGLE EVENT, UNWEIGHTED AND WEIGHTED)

Unweighted	0-15 km/h	16-25 km/h	26-40 km/h	> 40 km/h	All
Exposures	33%	57%	80%	92%	54%
AIS2+	56%	72%	87%	95%	80%
AIS3+	83%	76%	81%	97%	89%
Weighted	**0-15 km/h**	**16-25 km/h**	**26-40 km/h**	**> 40 km/h**	**All**
Exposures	31%	47%	70%	81%	45%
AIS2+	46%	56%	80%	88%	67%
AIS3+	94%	88%	56%	98%	83%

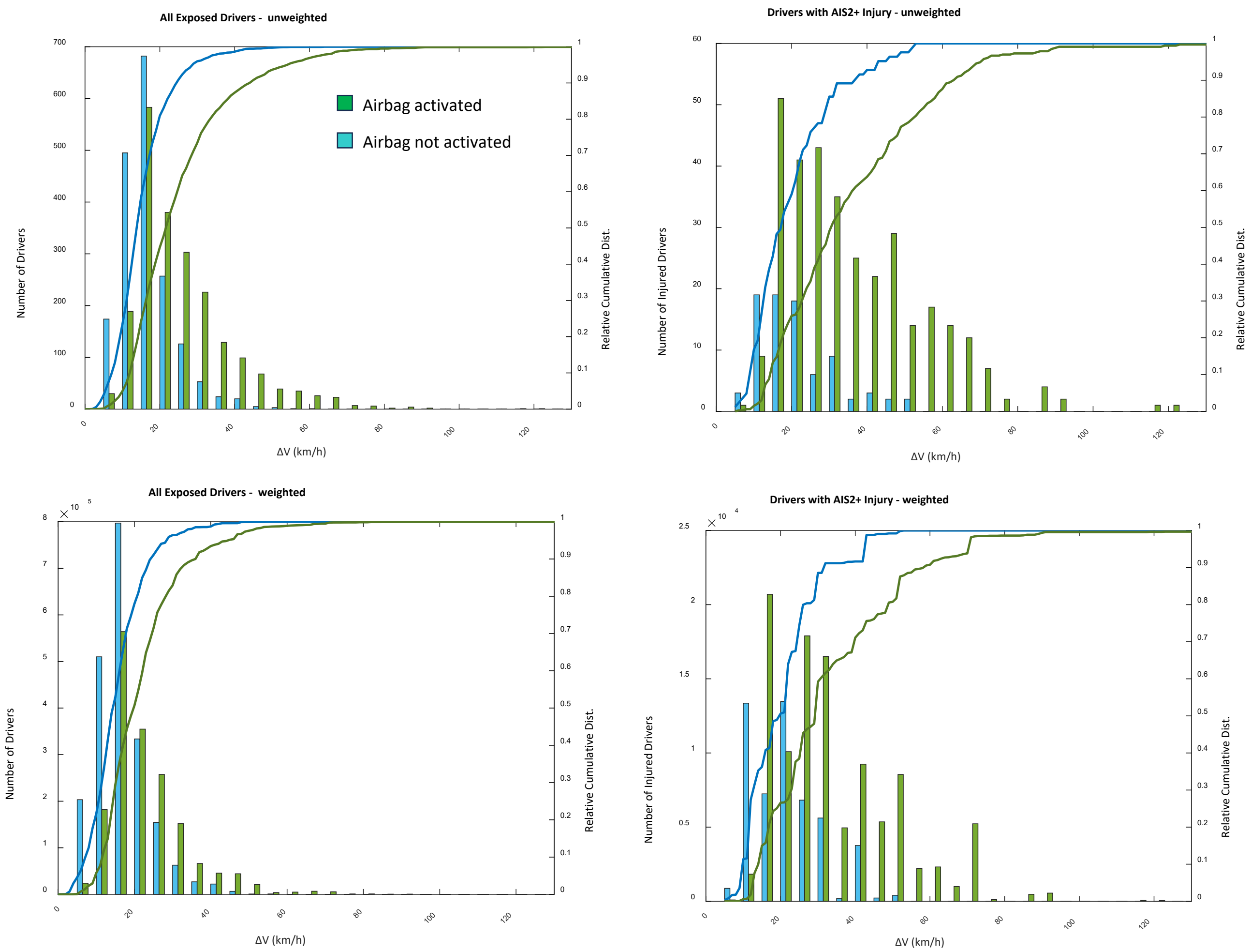

Fig. 2. Distributions of ΔVs for belted drivers in single-event frontal collisions in MY2002+ vehicles in CISS 2017-2022 (left), and distributions of ΔVs for the subset that experienced AIS2+ injury (right). Top: unweighted data. Bottom: weighted data. Colour-coded by airbag activation status. Bars represent raw data and lines represent the cumulative data.

Figure 3 shows the AIS2+ injury rate, stratified by age, stature, and Body Mass Index (BMI). The AIS2+ injury rate was calculated as the proportion of exposures within each age, stature, or BMI strata (bin) that experienced AIS2+ injury. (In other words, this is the same concept as the *risk* calculation in Table III). Appendix A shows the injury rate stratified by ΔV. Appendix B shows distributions of selected driver characteristics (age, stature, BMI) comparing exposures to AIS2+ injury cases. The age distribution for collision exposures tends to be skewed towards the young. However, risk tends to increase with increasing age. As a result, the age distributions tend to shift towards older ages for cases with injuries, though given the high rate of exposure to the young the net effect is a relatively flat (or bimodal) age distribution among the injury cases. The risk is relatively flat as a function of stature, causing the distributions of stature for the exposures and the injury cases tend to mirror each other (exhibiting no noticeable shift). Examining males and females combined, risk tends to be relatively flat as a function of BMI until around BMI of 35 (afterwards there is a noticeable increase). As a results, the BMI distributions largely mirror each other, with a subtle but noticeable shift towards higher BMI for injured drivers (median BMI 26 for exposures, 27 for AIS2+ injury cases). Of note, though, there tends to be a divergence in risk comparing females and males in the BMI range from 33 to 38.

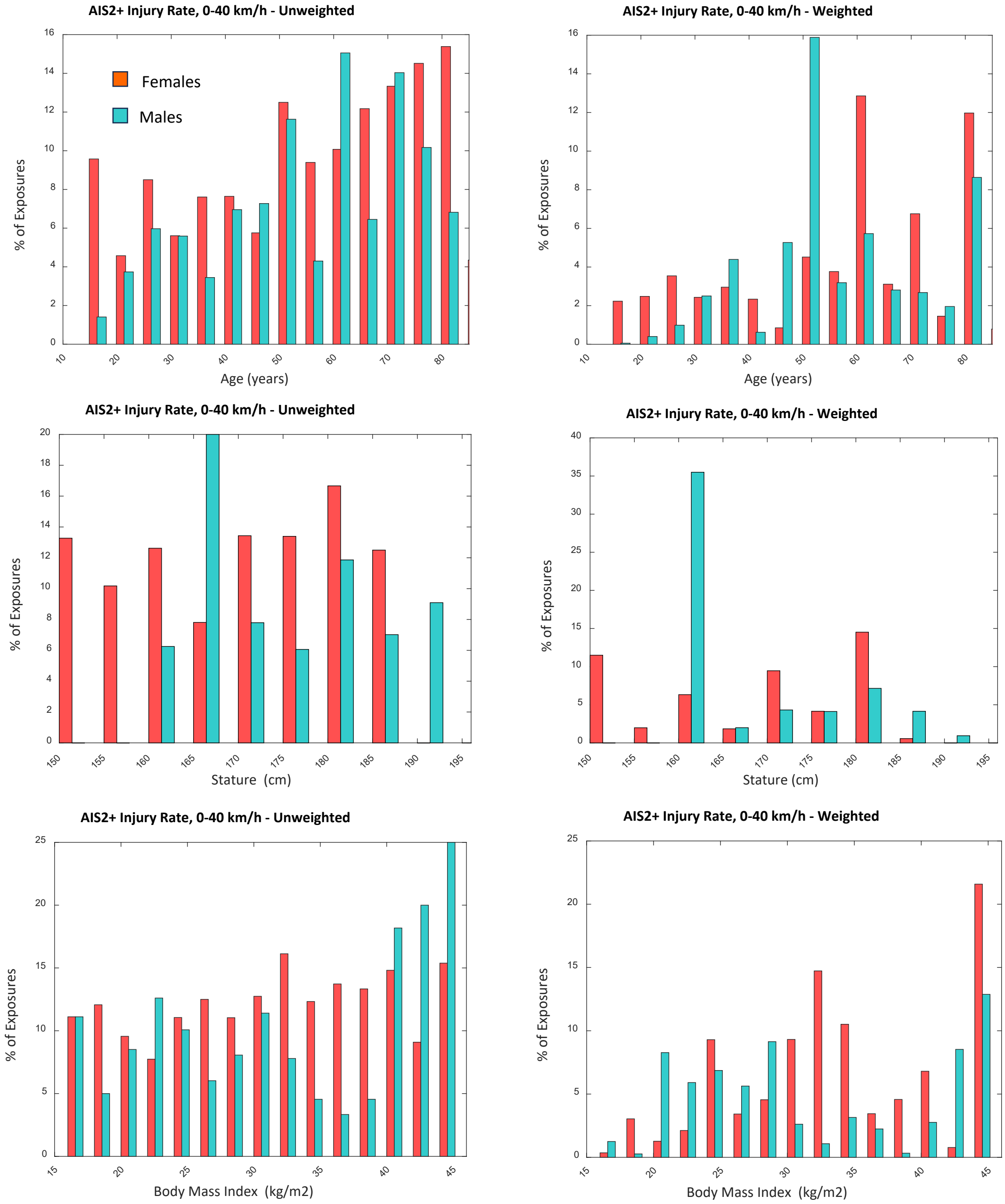

Fig. 3. AIS2+ injury rates by age (top), stature (middle), and BMI (bottom), for drivers in collisions with ΔV's from 0-40 km/h. Injury rates are calculated as the proportions of collision-exposed belted drivers in each bin that experienced AIS2+ injury. Single-event, frontal collisions in MY2002+ vehicles in CISS 2017-2022.

Figures 4 and 5 show the proportion of exposures exhibiting AIS2, 3, and 4+ injury by AIS body region and ΔV range. The head, thorax, and upper extremities tended to be among the most common body regions to exhibit AIS2+ across ΔV ranges, with lower extremity injury coming to prominence at ΔVs above 26 km/h and abdomen injuries appearing with greater frequency above 40 km/h.

To further contextualise the injury types that occur, Figure 6 shows the proportion of AIS2+ injury cases that exhibit the narrower subcategories of injuries described above. In the lower ΔV categories (0-40 km/h), the vast majority of AIS2+ injury cases (71-92%) only exhibit AIS2 injury. In contrast, 51% of AIS2+ injury cases >40 km/h exhibit AIS3+ injury. Among the lowest ΔV range (0-15 km/h), the most common injury types are AIS2 brain injury (mostly concussion diagnoses) and upper extremity injuries (mostly fractures). While brain and upper extremity injuries are still among the 16-25 km/h and 26-40 km/h ΔV ranges, they are surpassed by ribcage fractures (which also comprise the most common AIS3+ injury types). In the highest ΔV range the injury types become much more varied, with increasing frequency of thoracic organ injury, abdomen injury, and a variety of lower extremity injuries (pelvis, femur, tib/fib, and ankle).

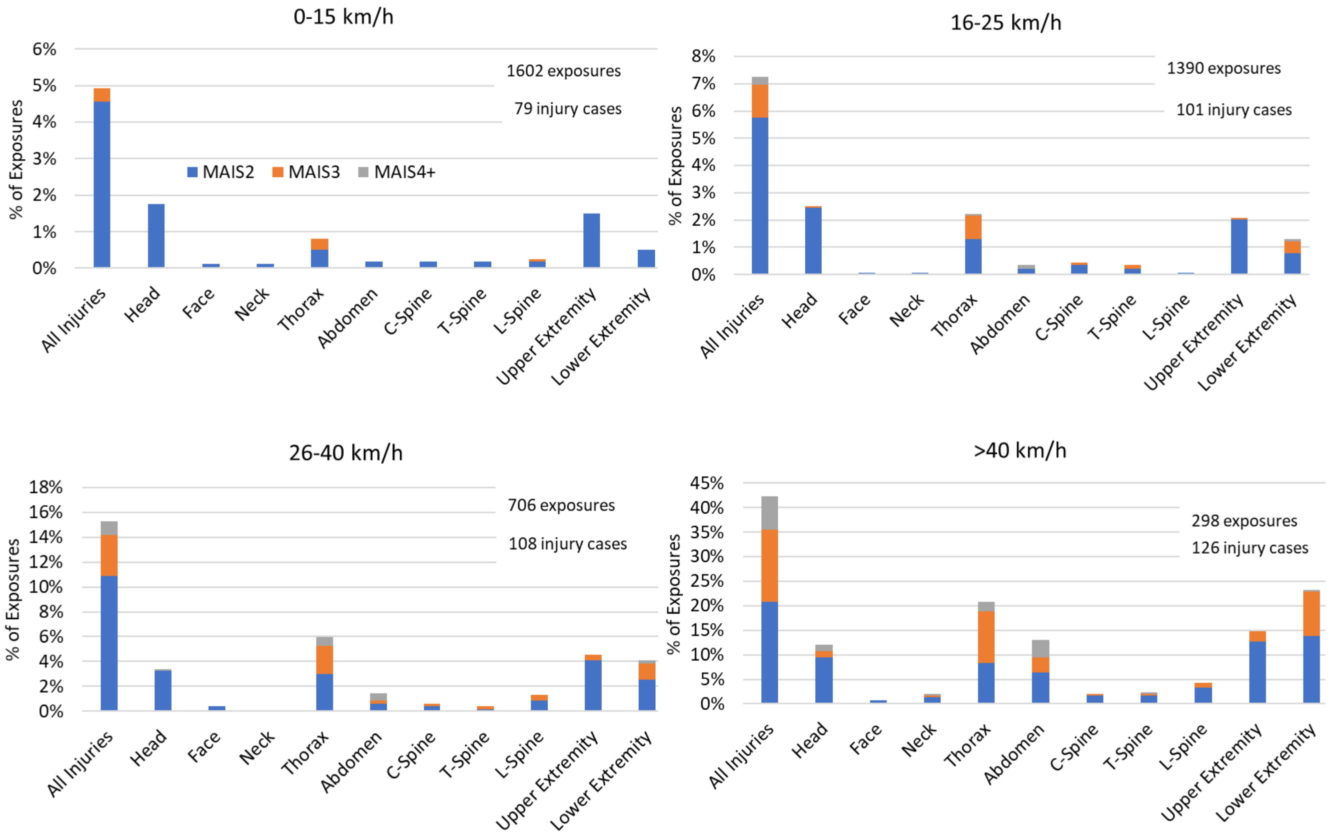

Fig. 4. Proportions of collision-exposed drivers that experienced various types of AIS2+ injury, by injured body region, injury severity, and ΔV range (unweighted). Note: Any one particular driver may only be counted within each body region bar once, but they may show up in multiple body region bars (in cases of multi-trauma across multiple body regions). (CISS 2017-2022, MY2002+, belted drivers, single-event frontal collisions.)

Finally, to provide context for thoracic injury risk associated with cases of pretensioner activation in low-severity collisions, cases counts and injury rates were tabulated for the two lowest ΔV categories, comparing cases with and without seatbelt pretensioner activation. Consistent with the airbag results shown above, cases with pretensioner activation generally had a higher rate of injury overall. This is likely due to the fact that collisions need to meet a certain detected collision severity in order to activate the pretensioners, causing the pretensioner-activated collisions to naturally comprise higher-severity collisions (with a higher risk of injury) within each ΔV category. Even with this, however, the per-crash risk of AIS2+ and 3+ chest injury in cases of pretensioner activation was very low (less than 3% for AIS2+; less than 1.5% for AIS3+; unweighted). Lower risks tended to be observed after applying case weights (Appendix C).

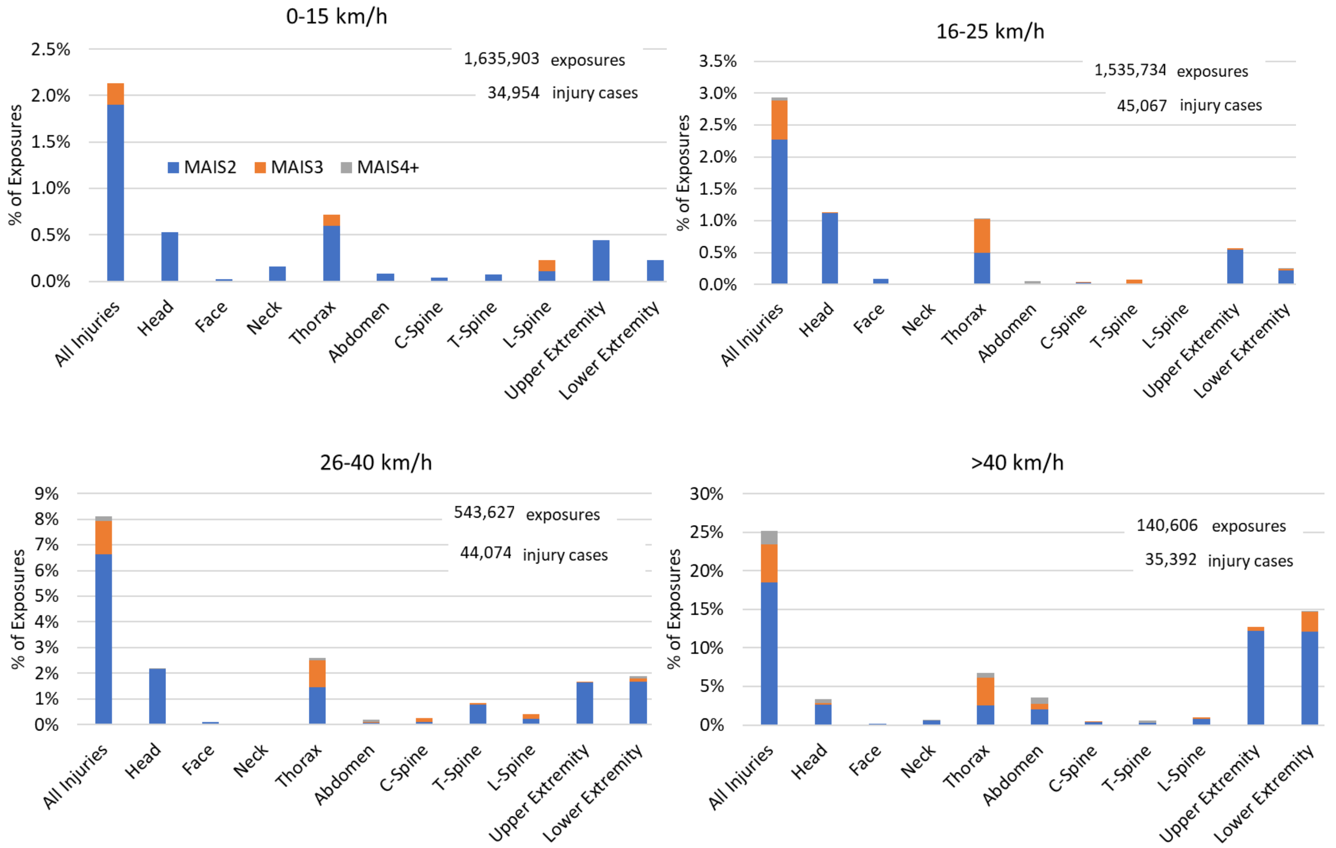

Fig. 5. Proportions of collision-exposed belted drivers that experienced various types of AIS2+ injury, by injured body region, injury severity, and ΔV range (weighted) in single-event frontal collisions in MY2002+ vehicles in CISS 2017-2022. Note: Any one particular driver may only be counted within each body region bar once, but they may show up in multiple body region bars (in cases of multi-trauma across multiple body regions).

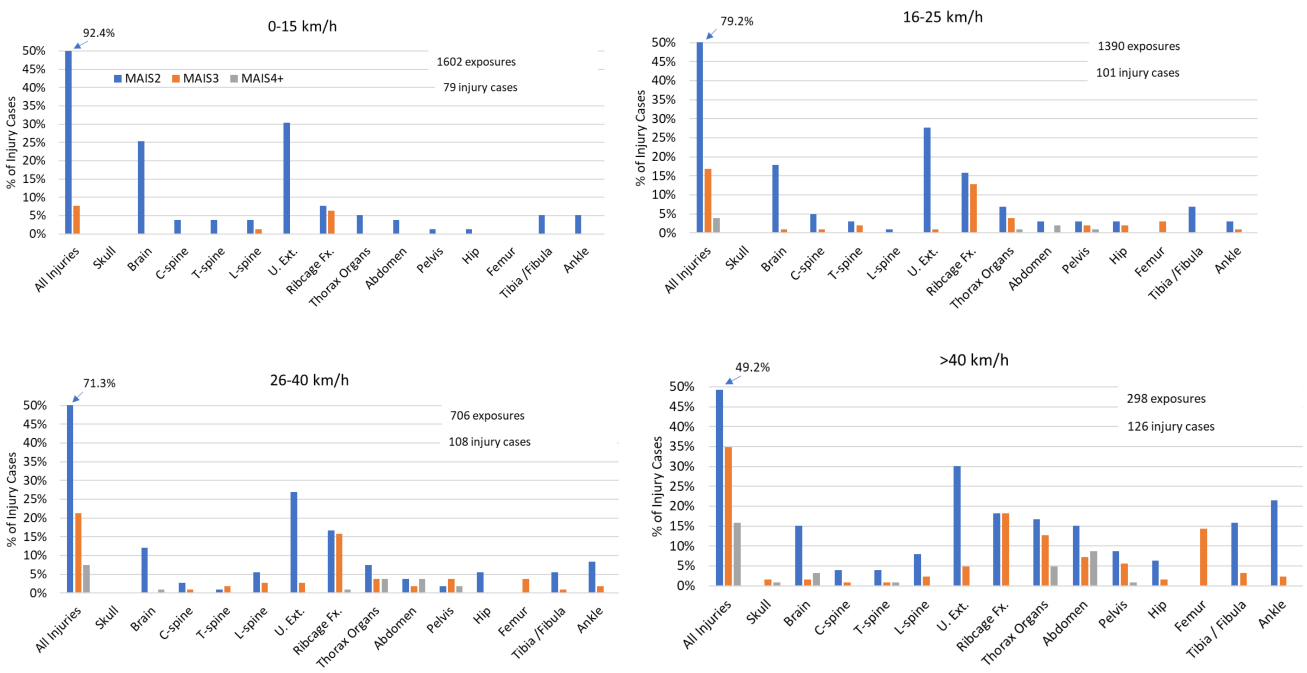

Fig. 6. Proportions of AIS2+ injured belted drivers that experienced various types of AIS2+ injury, by injury severity and ΔV range (unweighted) in single-event frontal collisions in MY2002+ vehicles in CISS 2017-2022. Note: Any one particular driver may only be counted within each injury type once, but they may show up across multiple injury types (in cases of multi-trauma across multiple injury types).

TABLE V
BELT PRETENSIONER ACTIVATION FOR THE LOWEST TWO ΔV CATEGORIES, BY INJURY TYPE
(CISS 2017-2022, MY 2002+, FRONTAL, BELTED DRIVER, SINGLE EVENT, UNWEIGHTED)

	0-15 km/h		16-25 km/h	
	Not Activated	Activated	Not Activated	Activated
Exposures (counts)	890	712	539	851
AIS2+	30	49	27	74
AIS2+ Chest	5	8	9	22
AIS3+	1	5	3	18
AIS3+ Chest	1	4	2	11
Risk of AIS2+	3.4%	6.9%	5.0%	8.7%
Risk of AIS2+ Chest	0.6%	1.1%	1.7%	2.6%
Risk of AIS3+	0.1%	0.7%	0.6%	2.1%
Risk of AIS3+ Chest	0.1%	0.6%	0.4%	1.3%

IV. DISCUSSION

As has been consistently observed throughout the field, the vast majority of collisions are relatively low speed [6-12]. In this dataset, 82% of police-reported tow-away frontal collisions occurred at or below 25 km/h, and 96% occurred at or below 40 km/h (weighted). Even though the per-crash injury risk in these low-to-moderate speed collisions is quite low (less than 10% risk for AIS2+ in 26-40 km/h crashes), the very high exposure counterbalances the low per-crash injury risk, resulting in 78% of AIS2+ injury cases (and 70% of AIS3+ injury cases) occurring at or below 40 km/h. Note that these are based on WinSmash-estimated ΔVs. Reference [9] reported that WinSmash tends to underestimate ΔV compared to Electronic Data Recorder (EDR), with a relationship that depends on collision type. Even if we were to add 10 km/h to the WinSmash estimates to account for this (similar to the mean offsets observed by Brumbelow), the data presented here still suggest that 50% of AIS2+ injury cases would occur at or below 35 km/h (with 78% occurring at or below 50 km/h).

The continuing prominence of injuries occurring in low-to-moderate speed collisions suggests that benefit may be drawn from prospective safety assessment that incentivises development of strategies to mitigate injuries in such collisions. While a necessary and admirable goal, however, this presents substantial challenges. First, although low-to-moderate speed collisions comprise a large portion of the injury cases (due to the very high exposure), the per-crash injury risk in such cases is already quite low. The good news is that even a small reduction in injury risk in such cases is likely to result in prevention of a substantial number of injuries (e.g., dropping from 8% to 6% AIS2+ injury risk in 26-40 km/h crashes means 1,800 fewer injured drivers per year, weighted). The challenge is that this requires very high precision in our injury prediction tools, with confidence that they can accurately discern such small changes in injury risk (when the baseline injury risk is already quite low). Occupant models such as ATDs and human body models should be critically evaluated for their biofidelity, sensitivity, and injury prediction precision at low-to-moderate loading severities before they are used for safety assessment in low-to-moderate speed collisions. This also presents a fundamental challenge for reference data available to judge injury prediction precision. To check injury risk prediction for a single exemplar load case with an anticipated 10% risk of injury, one would need to perform at least 10 tests with post-mortem human surrogates (PMHSs), hoping to have one result in injury. Thorough validation would require data collection in many such load cases, to validate that the occupant model and injury risk functions are sensitive to changes in loading condition in the correct manner. This suggests that an infeasible amount of new PMHS tests would be needed to thoroughly validate injury risk prediction tools for low-to-moderate speed collisions, suggesting that novel means may be needed for such refinement and validation (e.g., statistical tools that can combine information from multiple experimental, epidemiological, and simulation-based data sources, such as Bayesian analysis). As the field is rapidly advancing capabilities in tools such as human body models, this brings new opportunity to use these tools to supplement physical data to address areas where the resolution of physical data is limited by practical concerns in testing. In addition, it is possible (if not likely) that in these low-to-moderate speed collisions factors such as occupant position, muscle activation, and interaction with the vehicle systems (e.g. pedal engagement) may play a role in determining injury outcome. Again, it is daunting to envision how the diversity of injury causation scenarios may be incorporated to assess the robustness of protection provided by safety systems, though it may be possible via simulation to augment physical tests.

The second major challenge lies in anticipating potential adverse consequences for prospective safety assessment targetting low-to-moderate speed collisions. In particular, if one were to add a series of low-to-moderate speed tests with very conservative injury risk targets to an existing safety assessment programme, this may prompt manufacturers to incorporate additional restraint adaptation to decrease the forces applied to the occupant during the low-to-moderate speed tests (while still maintaining appropriately-high forces in higher speed tests [14-23]). This may very well be a beneficial strategy, but also carries a risk of potentially increasing injury risk if the collision severity or occupant mass is misclassified by the vehicle's restraint control system (e.g., mistakenly classifying as a low speed collision and decreasing the restraint force, when in fact the collision is higher severity [24]). To mitigate the risk of this type of adverse consequence, any assessment programme that may incentivise adaptive restraints must also include rigorous assessment of a vehicle's sensing and classification of collision severity (including assessment of the robustness of classification across a range of potential collision severities and scenarios).

Overall, the age, stature, and BMI distributions of drivers that experienced AIS2+ injury tended to follow the distributions of those exposed to collisions. There was somewhat of a shift towards increased age among those injured, but since the exposure distribution was heavily biased towards the young this shift simply resulted in a levelling out of the age distribution among those injured. In other words, the age distribution is subject to the same interaction between risk and exposure as the ΔV distribution is. Even though elderly people tend to be at greater per-crash risk for many injury types [2], the greater crash exposure for the young counterbalances the difference in risk. As a result, there are as many (if not more) young people that experience AIS2+ injury as there are older people. This is also evident in the average ages shown in Tables I and II. Even in the low ΔV categories, the average age of those injured was around 50 years old. These data suggest that low-to-moderate speed collisions are not just a concern for the elderly, but are a concern for all occupants (due to the interplay between exposure and risk). Similarly, although the BMI distribution for the AIS2+ injury cases is shifted slightly higher than those exposed, the BMI (and stature) distributions largely mirror the population distributions of those exposed to collisions. In other words, all people, of all shapes and sizes, are affected by collisions. While daunting, this further highlights the potential value of advanced tools that may aid in evaluation of the robustness of protection offered by safety systems across the population (e.g., morphable human body models), and highlights the need to avoid making safety decisions based on narrow ranges of occupant characteristics at the potential expense of the rest of the population.

In the low-to-moderate speed collisions (40 km/h and below) the most common AIS2+ injury types were injuries to the brain, ribcage, and upper extremities. This is consistent with [7-8], who found similar trends in relative frequency within GIDAS. Most of the AIS2 brain injuries were concussions. While we recognise that there is still some debate regarding concussion in such field data, for now the best that we can do is suggest priorities based on the data that is available. The observation that AIS2 brain injuries occur with relatively high frequency in both European and U.S. datasets suggests that these injuries are not simply an artifact of diagnosis practices within a particular healthcare system. Instead, these data suggest that either AIS2 brain injury should be prioritised alongside chest injury in prospective evaluations of low-to-moderate speed collisions, or further investigation is warranted to understand the nature and mechanisms of AIS2 brain injuries occurring in the available field data datasets in the U.S. and Europe. Similarly, upper extremity injuries continue to persist across datasets and collision severity ranges. The vast majority of these are fractures, particularly wrist, shoulder (including clavicle), and forearm. While upper extremity injuries have traditionally been deprioritised for assessment in fontal impact safety evaluation programmes, they carry a high risk of permanent medical impairment [26] and will likely continue their prominence until addressed by the field.

Most cases resulting in AIS2+ injury exhibited frontal driver airbag activation. Note that this should not be taken to mean that the airbags cause the injury. Airbag control units are programmed to deploy the airbag once a certain collision severity threshold is reached. As a result, airbag deployment can be considered a surrogate indicator for overall collision severity. Thus, it is logical that injuries occur more often in cases with airbag deployment, where the collision severity is higher than cases without airbag deployment. This is consistent with the findings of [8] from GIDAS, who observed similar rates of airbag deployment among exposures and cases of AIS2+ injury. Of note, even in the 0-15 km/h range where an airbag may not be expected to deploy, a majority (56%) of the unweighted AIS2+ injury cases exhibited airbag deployment. This may indicate that at least a portion of these cases may be of a nature where WinSmash-estimated ΔV does not capture the full picture of the severity of the crash [8-9][25]. In these instances, observing airbag activation provides valuable additional context on the overall crash severity, suggesting that a majority of AIS2+ injury cases (even in relatively low speeds) occur with collision pulses great enough to trigger the airbag control algorithms. As a result, these data suggest that prospective safety assessment for low-to-moderate speed collisions should target speeds that are likely to result in airbag activation (as opposed to very, very low speeds where the airbag would be less likely to deploy). Further, even though not specifically investigated in this study, it is possible that the side airbags may also affect injury risk in the subset of crashes that were oblique or resulted in vehicle rotation. Future work should include study of the effects of the entire restraint system in the variety of low-to-moderate speed collisions that occur in the field. Additionally, future work should include continued investigation of how these trends in exposure and injury may change with increased market penetration of collision avoidance technology such as automatic emergency braking (AEB) [27].

Finally, given prominence of ribcage fractures in relatively low speed collisions, it is likely that ribcage fractures will be a high-priority target for prospective safety assessment below 40 km/h. This will likely prove challenging for prediction with traditional tools (ATDs or human body models), as the per-crash thoracic injury risk in these collisions is already quite low (below 3%, Figure 5). Thus, we anticipate that additional research effort will be needed to refine and validate thoracic injury prediction for ATDs and HBMs for low loading severities and injury risks. One such way to check the reasonableness of these tools will be to study their chest injury risk prediction in scenarios that have been documented to carry low injury risk. These data show that in low speed collisions (25 km/h and below), the chest injury risk is quite low even if the seatbelt pretensioner is activated. This means that if an ATD or HBM is tested under static deployment with a typical pretensioner, then it should predict a very low risk of chest injury (less than 3%). If it predicts greater risk, then either the tool or its Injury Risk Function (IRF) likely needs to be refined to achieve realistic thoracic injury risk prediction under low severity loading.

V. CONCLUSIONS

As has been observed consistently in the past, the vast majority of collisions are of low-to-moderate speed. Injuries occur as a result of the combination of exposure and per-crash injury risk. Even though the per-crash injury risk in low-to-moderate speed collisions is quite low, exposures are dominated by low-to-moderate speeds. The net effect is that most injury cases occur in low-to-moderate speed collisions. Overall, these results and trends are consistent with those observed in the past [9-12], as well as those observed recently in GIDAS [7-8], suggesting that the observations described here are characteristic of collisions in general, and are not uniquely tied to any one dataset or locale. Occupant characteristics of those injured largely mirror those exposed to collisions, with the exception of a flattening of the age distribution and a slight shift towards higher BMIs. Most crashes that result in AIS2+ injury exhibited front driver airbag activation, suggesting that prospective safety assessments should target low-to-moderate speed collisions of high enough severity as to consistently trigger airbag activation. The 26-40 km/h ΔV range may be a reasonable range to target, as it resulted in consistently high airbag activation (70%, weighted). The most common AIS2+ injuries in low-to-moderate speed collisions (≤40 km/h) were AIS2 brain injury, ribcage fractures, and upper extremity fractures. Prospective safety assessment for low-to-moderate speed collisions is likely to prompt increased use of restraint adaptation technology to decrease forces applied to the occupant in low-to-moderate collision severities. Such assessments must be accompanied by robust evaluation of the vehicle's collision severity sensing and classification system (and potentially the sensing and classification system for occupant mass) to ensure that there are no adverse consequences with misclassification. The other key challenge will lie in refining and validating occupant injury prediction tools to discern small changes in injury risk in low-to-moderate speed collisions. This may be aided by augmenting traditional means for ATD and HBM validation with common-sense, pragmatic approaches such as checking the reasonableness of prediction in scenarios that are documented to be of low risk (e.g., under static deployment of typical pretensioners, or comparing to non-injurious volunteer tests).

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VII. Appendix A: Injury Rates By ΔV

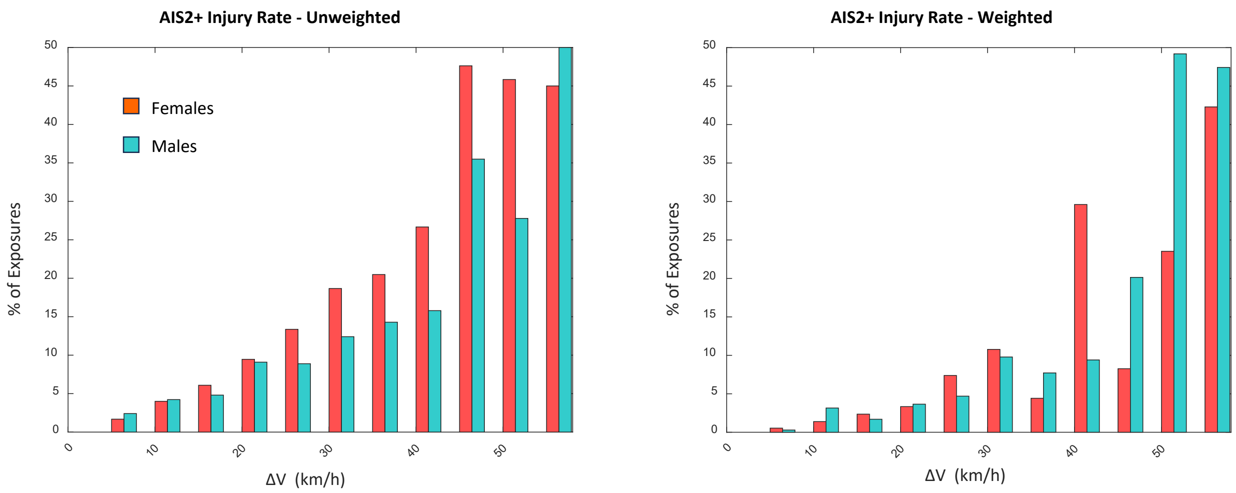

Fig. A1. AIS2+ injury rates by ΔV. Injury rates are calculated as the proportions of collision-exposed belted drivers in each bin that experienced AIS2+ injury. Single-event, frontal collisions in MY2002+ vehicles in CISS 2017-2022. Left: Unweighted. Right: Weighted.

VIII. Appendix B: Occupant Characteristic Distributions

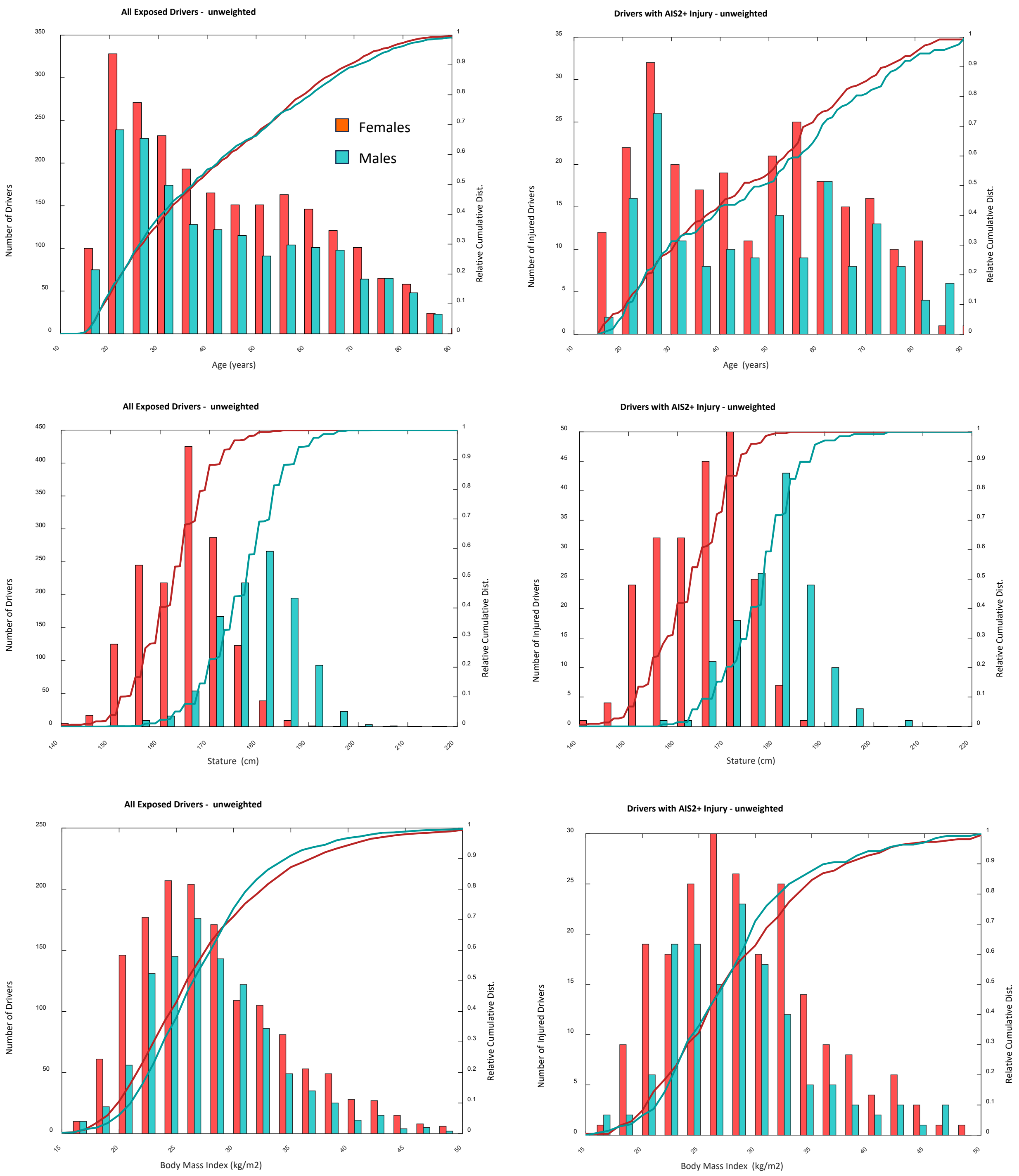

Fig. B1. Distributions of driver age (top) stature (middle), and body mass index (BMI, bottom) for belted drivers in single-event frontal collisions in MY2002+ vehicles in CISS 2017-2022 (left), and distributions for the subset that experienced AIS2+ injury (right). All ΔV's. All data shown are unweighted. Bars represent raw data and lines represent the cumulative data.

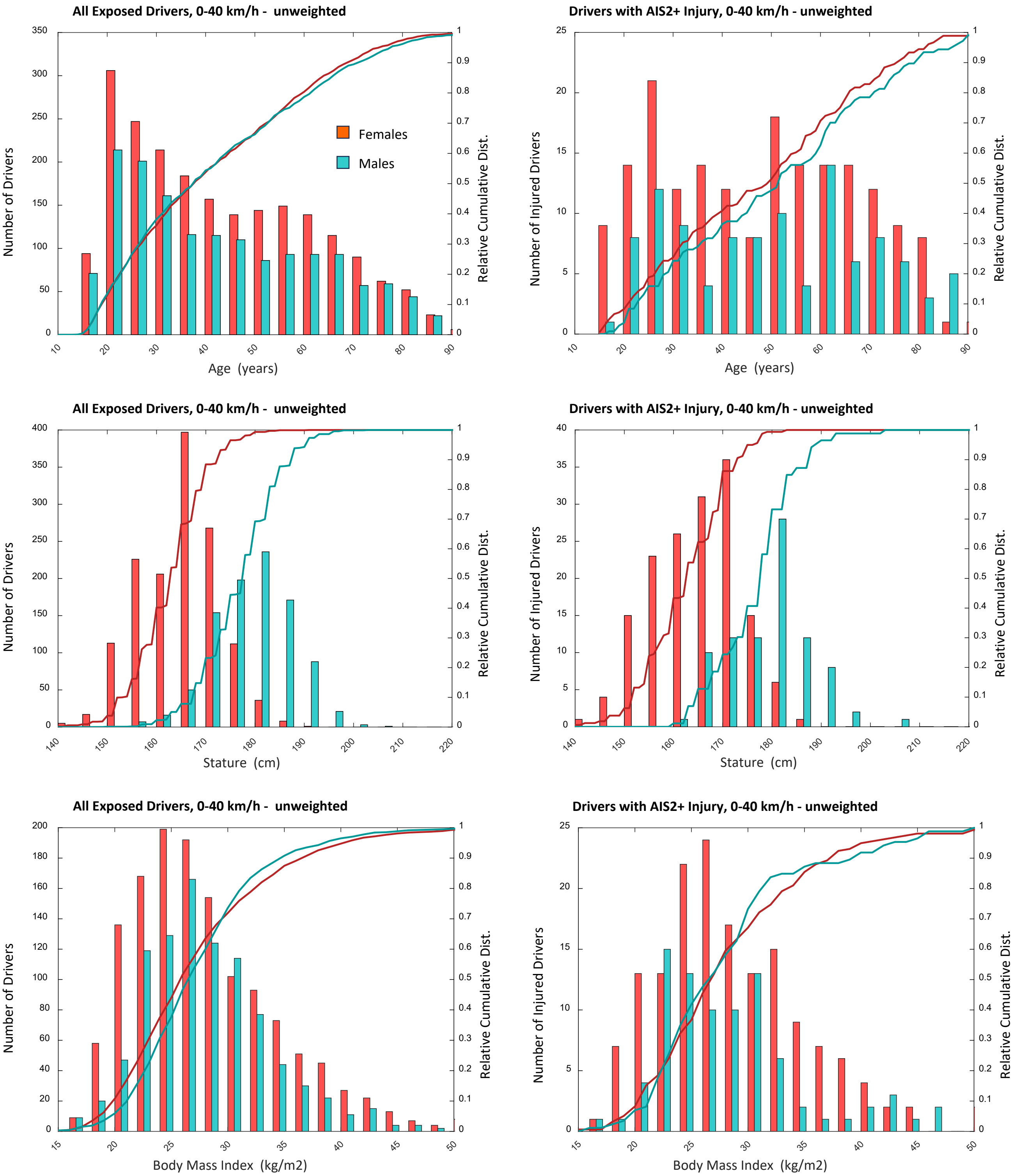

Fig. B2. Distributions of driver age (top) stature (middle), and body mass index (BMI, bottom) for belted drivers in single-event frontal collisions in MY2002+ vehicles in CISS 2017-2022 (left), and distributions for the subset that experienced AIS2+ injury (right). ΔV: 0-40 km/h. All data shown are unweighted. Bars represent raw data and lines represent the cumulative data.

IX. Appendix C: Pretensioner Activation for 0-15 km/h and 16-25 km/h, Weighted

TABLE C1
BELT PRETENSIONER ACTIVATION FOR THE LOWEST TWO ΔV CATEGORIES, BY INJURY TYPE
(CISS 2017-2022, MY 2002+, FRONTAL, BELTED DRIVER, SINGLE EVENT, WEIGHTED)

	0-15 km/h		16-25 km/h	
	Not Activated	Activated	Not Activated	Activated
Exposures (counts)	946,768	689,136	699,306	836,428
AIS2+	15,865	19,089	15,837	29,231
AIS2+ Chest	7,320	4,408	4,214	11,545
AIS3+	244	3,599	924	9,159
AIS3+ Chest	244	1,757	171	7,996
Risk of AIS2+	1.7%	2.8%	2.3%	3.5%
Risk of AIS2+ Chest	0.8%	0.6%	0.6%	1.4%
Risk of AIS3+	0.0%	0.5%	0.1%	1.1%
Risk of AIS3+ Chest	0.0%	0.3%	0.0%	1.0%