

Thoracolumbar Spine Injuries in Car Crashes

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Abstract While thoracolumbar (TL) spine injuries have increased in relative importance, they have been subject to limited test methods and injury criteria developments. Using real-world crashes from Volvo Cars Traffic Accident Database, a two-part study was carried out: a statistical analysis to establish the correlation between influencing factors to the accident occurrence; and an in-depth data study to identify and categorise AIS2+ TL spine fractures.

Most of the thoracolumbar fractures occur in the area of transition between the thoracic and lumbar spine. Compression is the most common AIS2+ TL spine fracture type, followed by anterior wedge. The occurrence of these is mainly in crashes with a main force component towards the front or the undercarriage. In side impacts, transversal processes fractures are the most frequent injuries.

There is an over-representation of these injuries in complex events, such as multiple impacts and multiple events, including run-off-road, rollover and turnover. In the cases of pure frontal impacts, the crash severity is typically high, with a large front structure engagement exerting the occupant for high accelerations.

The character of the TL spine fractures, together with the situations of occurrence; provide important insights into likely occupant loading mechanisms, enabling important steps towards methods and criteria addressing these injuries.

Keywords Car crashes, crash statistics, spine fractures, thoracolumbar spine, real world data analysis.

I. INTRODUCTION

Thoracic and lumbar spine injuries to a car occupant can occur in a variety of crash situations [1-5]. Studies have shown that the thoracic and lumbar spinal injuries have not decreased over the years to the same extent as compared to the overall injury reduction. Comparing crashes involving Volvo cars in Sweden in 2001–2005 to those in 1991–1995, only a slight reduction of thoracic and lumbar spine injury rate was seen, in contrast to the significant MAIS2+ injury rate reduction [2]. Wang *et al.* [6] reported that among drivers and front-seat passengers admitted to hospital after relevant motor vehicle crashes, the occurrence of spine fractures increased between 1994 and 2002. Pintar *et al.* [4] reported a relative increase of incidence of thoracolumbar (TL) spine injuries with newer model year compared to other crash modes in frontal crashes. Studying US National Automotive Sampling System (NASS) data for 1998–2007, Doud *et al.* [7] found increases in the incidence of thoracolumbar injury.

Most studies have investigated frontal crashes [4][8-11], discussing the influence of vehicle structure stiffness, seat design and seatbelt usage and design. Adolph *et al.* [11] highlighted an association with abdominal injuries, and saw a trend of probable late acceleration peak in the crash pulse in frontal impacts. However, thoracic and lumbar spinal injuries are seen in all crash situations [2][12-13]. In Jakobsson *et al.* [2], 21,034 adult occupants in Volvo cars during 1991–2005 were studied, identifying an over-representation of AIS2+ thoracic and lumbar spine injuries in crashes involving run-off-road, multiple impacts and multiple events. Based on in-depth studies on 95 thoracic and lumbar spine injured occupants, spinal injuries were seen as a result of extensive forward bending of the upper body during impact, emphasising the role of occupant posture during vertical load transfer through the spine at impact. For their research, [13] queried NASS-CDS for far-side occupants in lateral impacts to investigate the occurrence of lumbar spine injuries, concluding that the severity of the impact is of importance for the occurrence of lumbar spine injuries.

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Most studies report that the TL spine injuries typically occur in the lumbar spine and/or at the transition between the thoracic and lumbar spine [2][4][11]. Studying frontal impacts in the USA, [4] reported that burst type fractures predominantly occur at T12, L1 or L5, while anterior wedge fractures were most commonly seen at L1. Another study [11] reported burst, compression and dislocation fractures from the studied subset of frontal crashes in Europe. Considering the whole spectra of accident situations, [2] identified compression fracture as the most common fracture type, followed by anterior wedge fracture, burst and transversal processes fractures.

Pioneering work to investigate the response of the vertebral column was carried out by [1]. They identified an axial force along the spine and its load on the seat pan during planar motion. They emphasised the importance of spinal curvature, acknowledging that the anthropometric dummies did not have this curvature. In the 1970s, a mathematical model validated for vertical accelerations [14] was used to predict the compressive force along the vertebral column, as well as seat pan loading when exposed to a frontal crash scenario [1]. More recently, [15] investigated the capability of the detailed FE-model GHBM (Global Human Body Model Consortium) to replicate compression-related lumbar spine fractures. Duma *et al.* [16] investigated the biomechanical responses of the lumbar spine in dynamic compression deriving the threshold levels as a combination of axial loads and bending moments. They stated that the mechanical stability of the lumbar spine is critical in relation to the tolerable compressive loads. More recent experiments on post-mortem human subjects' (PMHS) spinal segments performed by [17] derived peak force estimations as a function of likely probability of injury and specified a risk curve of injury when studying biomechanics of human thoracolumbar spinal column trauma from vertical impact loading. In addition, [18] developed a drop-tower test method to evaluate pelvis acceleration as an indirect measure of spinal loads, as a simplified test to address the occupant loading mechanisms related to vertical loads through the vehicle, typically occurring during rollover events, free flight and interaction with ditches and similar.

Today, no standardised test procedures include evaluation of spinal loads, and comparably limited research has been performed to establish criteria and test methods evaluating risk of TL spine fractures in car crashes. Real-world data, including all types of crashes, can provide important information towards development of such methods, by providing insight into the frequency and types of injury, including potential occupant loading mechanisms. Hence, the objective of this study is to identify and categorise AIS2+ thoracic and lumbar spine fractures from car crashes based on in-depth data analyses, and to put this into the overall injury context by statistical analysis of a larger dataset. Specifically, the different types of fracture are put in a context of potential vehicle loading situations and influencing factors, helping to establish important areas of developments for enhanced occupant protection.

II. METHODS

Using real-world crashes from Volvo Cars Traffic Accident Database, a two-part study was carried out: a statistical analysis to relate influencing factors to the occurrence of thoracolumbar (TL) spine injuries, and an in-depth case analysis in order to identify and categorise AIS2+ thoracic and lumbar spine injuries. In addition, three of the cases are presented to provide insight into different accident situations resulting in the same principal TL spine fracture type.

Volvo Cars' Statistical Accident Database contains Volvo passenger cars in Sweden, collected based on repair cost level (currently €4500). The level has been adjusted over the years to reflect and keep the impact severity for different crash modes stable. Volvia (If P&C Insurance) identifies the crash and Volvo Cars Traffic Accident Team sends out questionnaires to the occupants involved. Those who respond to the questionnaire are included in the database. Detailed information about the database is found in [19]. Since Volvo cars account for almost 25% of all passenger cars in Sweden, and all new Volvo cars are insured by Volvia for at least 3 years, the database is quite representative for modern passenger cars involved in moderate to severe crashes in Sweden.

Statistical analysis

Restrained occupants of age 15 or older (15YO+) in cars of model years 1999–2013 were selected for the analysis. Occupants with unknown AIS severity injury data were excluded, resulting in a total of 13,230 occupants. Of these, 382 (2.9%) sustained an injury of AIS2 or more. A further 4,231 sustained AIS1 injuries only,

while the remaining were uninjured. Among the AIS2+ injured occupants, 129 sustained at least one AIS2+ injury to the spine. Of these, 95 occupants sustained at least one AIS2+ injury to the thoracic or lumbar section of the spine. Of the remaining 34 AIS2+ spinal injured occupants, 23 occupants sustained injuries to the cervical spine only, two sustained injuries to sacrum only, and the rest had unspecified spinal injuries. Nine occupants sustained AIS2+ injuries to both TL spine and cervical spine.

For the 95 occupants sustaining AIS2+ TL spine fractures, a total of 103 AIS2+ injuries were reported. Of these, 43 were of severity AIS3, one of severity AIS4 and the rest (58%) of AIS2. The majority (58%) of the injuries were reported as lumbar spine injuries (L1-L5), while 31% and 11% were located in the lower thoracic spine (Th7-Th12) and upper thoracic spine (Th1-Th6), respectively. Among the 95 AIS2+ TL spine injured occupants, only 28 (29%) also sustained AIS2+ injuries to the thorax, abdomen or pelvis.

Descriptive occupant statistics of the overall occupant sample and the TL spine fractured occupant sample are shown in Tables I and II, respectively.

TABLE I
OCCUPANT CHARACTERISTICS' DISTRIBUTION OF THE 13,230 OCCUPANTS

	Gender	Mean age \pm stdev	Mean stature \pm stdev	Mean weight \pm stdev
Male	64%	46.0 \pm 17.3 y	179.7 \pm 7.1 cm	83.9 \pm 16.6 kg
Female	36%	45.6 \pm 17.1 y	166.6 \pm 6.2 cm	66.7 \pm 13.7 kg

TABLE II
OCCUPANT CHARACTERISTICS' DISTRIBUTION OF THE 95 OCCUPANTS WITH AIS2+ TL SPINE FRACTURES

	Gender	Mean age \pm stdev	Mean stature \pm stdev	Mean weight \pm stdev
Male	73%	47.7 \pm 16.9 y	181.6 \pm 6.8 cm	86.4 \pm 9.8 kg
Female	27%	54.2 \pm 20.1 y	167.1 \pm 5.9 cm	68.5 \pm 9.7 kg

In the statistical analysis, the distribution and influence of accident type, seating position and occupant factors were studied. AIS2+ TL spinal injury rate is defined as the number of occupants with AIS2+ thoracic or lumbar spine injuries divided by the total number of occupants (injured as well as uninjured) in the group considered. MAIS2+ injury rate per body region is the number of occupants with a maximum injury of AIS2 or higher for the body region concerned divided by the total number of occupants. MAIS2+ injured occupants are the number of occupants with a maximum overall body injury of AIS2 or higher.

In-depth data analysis

Available information, including medical records from hospitals, questionnaires from the occupants and car damage information, were studied in detail for a selection of occupants with AIS2+ TL spine fractures. For 72 occupants, enough information was available to clearly understand the accident sequence. These were included in the in-depth data analysis. For 53 of these occupants, the medical data was detailed enough to provide information on exact injury location and fracture type. In the in-depth data subset, 74% are drivers, 18% are front passengers and 8% are rear-seat passengers. Descriptive statistics of occupant characteristics are shown in Table III.

TABLE III
OCCUPANT CHARACTERISTICS' DISTRIBUTION OF THE 72 OCCUPANTS IN THE IN-DEPTH DATA

	Gender	Mean age \pm stdev	Mean stature \pm stdev	Mean weight \pm stdev
Male	72%	49.3 \pm 16.7 y	181.0 \pm 6.7 cm	86.0 \pm 10.0 kg
Female	26%	53.2 \pm 20.0 y	166.9 \pm 5.0 cm	66.5 \pm 8.1 kg

Based on the accident description and the car damages, the cases were categorised with respect to the estimated main loading directions onto the car during the crash sequence. The term *direction-of-impact* was created to describe this. The categories Front, Side, Rear and Vertical represent the main loading directions for the cars' interaction with opponent vehicles or the environment. Vertical direction-of-impact is typically undercarriage interaction with the ground/road. In cases with undercarriage interaction in combination with significant longitudinal loading, shown by frontal airbag activation, the cases were classified as Front and

Vertical as a combined *direction-of-impact*. For rollover crashes, the category Rollover is used. In cases with multiple sequential impact directions, no attempt was made to establish the most likely spine fracture-causing *direction-of-impact*, hence all are included in the analyses as potential injury-generating mechanisms.

III. RESULTS

Statistical analysis

Figure 1 shows the MAIS2+ injury rates per body region for the 13,230 occupants in the total dataset. Thoracolumbar (TL) spine injury rate is shown separately, although included in the spine body region. Spine injuries are within the top three most frequently injured body region, emphasising the importance of addressing TL spine fractures, as they form a large proportion of the spine injuries sustained in crashes.

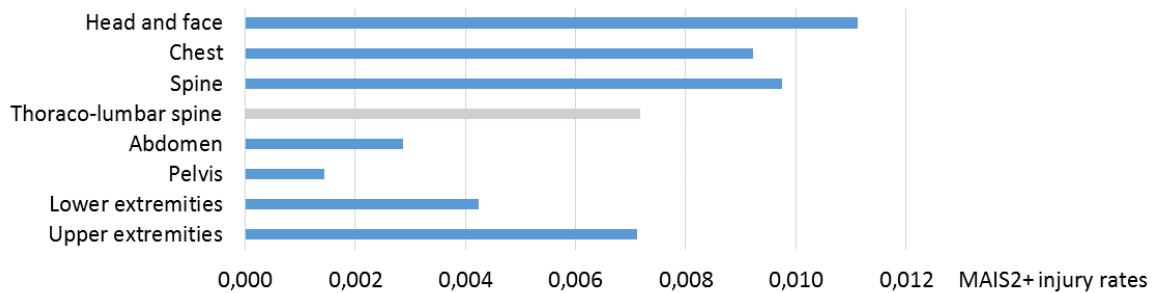


Fig. 1. Comparison of MAIS2+ injury rate per body region in the total dataset (N=12,230).

Figure 2 displays the distribution of accident types, comparing all occupants, all occupants with MAIS2+ injuries, as well as occupants with AIS2+ TL spinal injuries. For all three subsets, frontal impacts are the most frequent accident type. For the 95 occupants with AIS2+ TL spine injuries, frontal impacts account for 36%, followed by multiple impacts at 24%. Relative to overall MAIS2+ distribution, run-off road, multiple impacts, multiple events, sideswipe, roll and turnover all have a relatively high proportion of AIS2+ TL injured occupants, while the opposite is seen for pure frontal, side and rear-end impacts, as well as for large animal crashes.

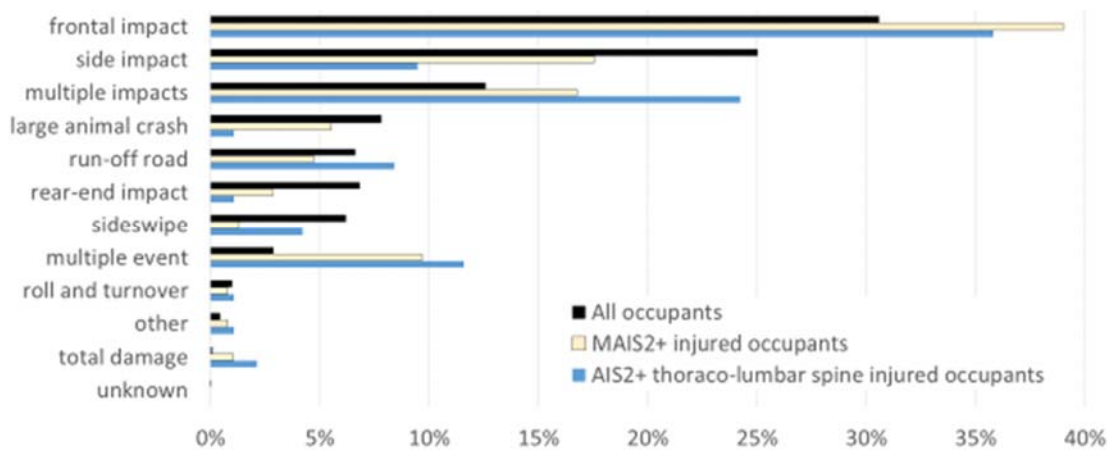


Fig. 2. Distributions of accident types comparing all occupants (N=12,230), all occupants with MAIS2+ injuries (N=382) and those with AIS2+ thoracolumbar spine injuries (N=95). Each category adds up to 100%.

In Fig. 3, the distribution of seating positions can be seen, comparing the three subsets of occupants. No major difference is seen in the pattern of TL spine injuries. It follows the general pattern of occupant distribution per seating position, which highlights that these injuries occur independent of seating position in the car, although the vast majority are seen among drivers due to exposure.

Figure 4 displays the injury rates, comparing men and women, and the overall injury rates (MAIS2+) to AIS2+ TL spine injury rates. It can be seen that the trend of AIS2+ TL spine injury rate deviates from the overall MAI2+ injury rate trend. There is a tendency for higher MAIS2+ rate for women as compared to men, while for the group of AIS2+ TL spine injuries an opposite tendency is seen.

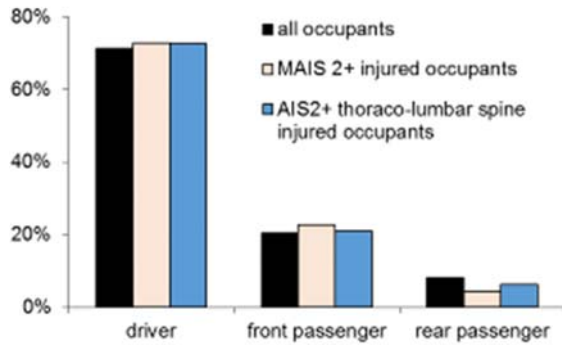


Fig. 3. Distribution of seating positions comparing all occupants (N=12,230), all occupants with MAIS2+ injuries (N=382) and those with AIS2+ thoracolumbar spine injuries (N=95). Each category adds up to 100%.



Fig. 4. MAIS2+ injury rates and AIS2+ thoracolumbar spine injury rates, comparing gender.

There is a larger proportion of elderly among those with AIS2+ TL spine injuries, which is in line with the overall picture of injuries sustained. Comparing the distributions due to occupant characteristics, such as stature and weight, there are some different distributions for the group with AIS2+ TL spinal injuries as compared to the overall group with MAIS2+ injuries. As showed in Figs 5 and 6, occupants of higher weight or increased stature, respectively, are somewhat more pronounced than what is seen among the overall MAIS2+ injured occupants. The same trend is seen when combining weight and stature into BMI. Almost all (99%) of the tallest group (181 cm) and 92% of the heaviest group (81 kg) are men.

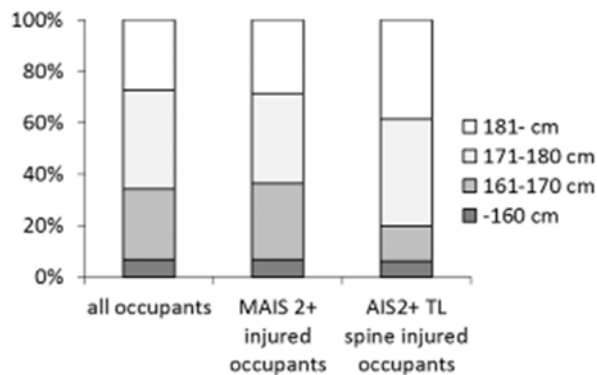


Fig. 5. Distribution of stature groups comparing all occupants, all occupants (N=12,230) with MAIS2+ injuries (N=382) and those with AIS2+ thoracolumbar (TL) spine injuries (N=95).

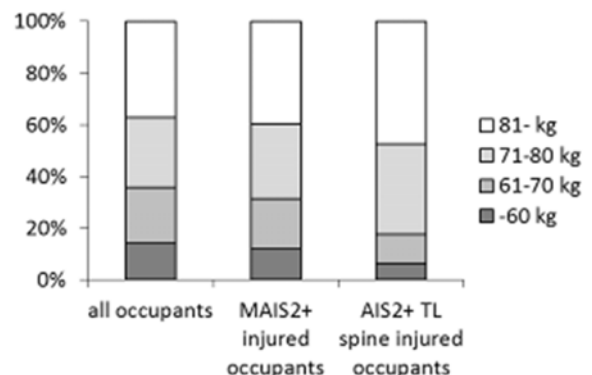


Fig. 6. Distribution of weight groups comparing all occupants, all occupants (N=12,230) with MAIS2+ injuries (N=382) and those with AIS2+ thoracolumbar (TL) spine injuries (N=95).

In-depth data analysis

Figure 7 displays the distribution of accident types for the in-depth data subset of AIS2+ TL injured occupants. Frontal impacts are most frequently seen, followed by multiple impacts, run-off-road events and side impacts. The in-depth data subset follows the distributions of the statistical data (Fig. 2), with a majority of frontal impacts, followed by multiple impacts and events.

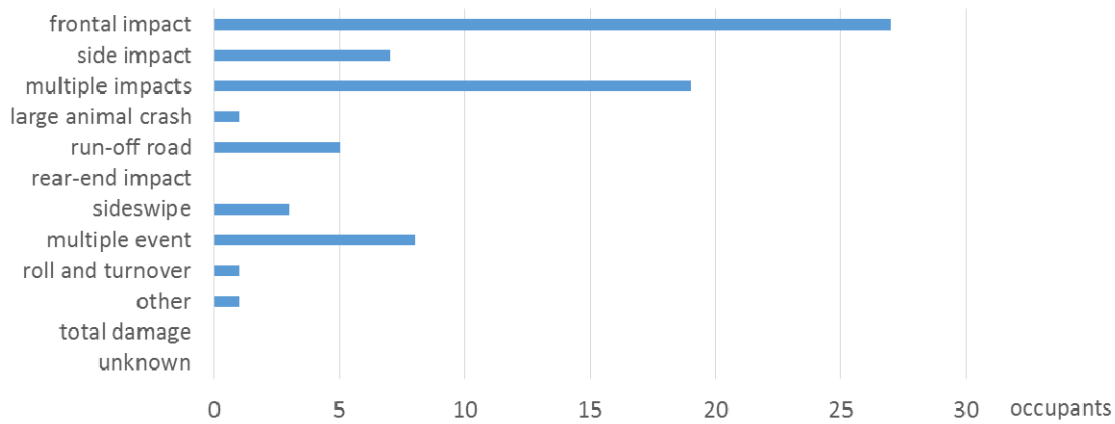


Fig. 7. Number of occupants (N=72) per accident type, in-depth data subset.

Using the created classification *direction-of-impact*, the cases are distributed as shown in Fig. 8. Cases with several *direction-of-impacts* are categorised as multiple *direction-of-impacts*. The only rollover case in the sample is included in this group as well. The three cases classified as Other are of a character that did not fit into any of the groups: one was a large-animal crash; the other two are run-off-road events with interactions with trees, mainly to the upper part of the car.

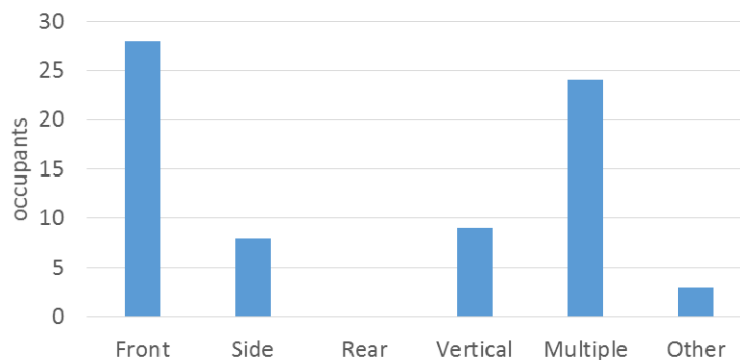


Fig. 8. Distributions of *direction-of-impact* for the cases (N=72) in the in-depth data subset.

As seen in Fig. 8, pure Front *direction-of-impact* is the most frequent group, with 28 cases in total. The majority of these are coded frontal impact as accident type. In addition, among the 24 cases with Multiple *direction-of-impacts*, 13 include a front direction component. Hence, 41 of the total 72 cases include a front direction component. In 21 of the 28 pure Front *direction-of-impact* cases, two-thirds or more of the vehicle’s front was engaged, and in most of these cases the deformation depth was 40 cm or more, causing the occupant to be exposed to large accelerations.

Vertical *direction-of-impact* is also pronounced, including 9 cases of pure vertical interactions and 19 cases where it is judged to be a part of the interaction during the accident sequence. They are found within several different accident types, including frontal impacts, run-off-road, multiple impacts and multiple events. Typical characteristics of the Vertical *direction-of-impact* is a run-off-road event with an interaction of the undercarriage with a ditch or stone, as the single event or as part of a multiple event.

Side *direction-of-impact* is the third most prominent category, with eight pure Side *direction-of-impact* and five cases where it occurs as one of several events (one of these features impacts to both sides). Among the pure Side *direction-of-impact* cases, two of the three far-side cases were of high severity and four of the five near-side cases included intrusion into the compartment area at the site of the occupant concerned. No pure cases of Rear *direction-of-impact* were seen in this data subset. Rear *direction-of-impact* was part of 9 of the cases coded as Multiple *direction-of-impact*.

The 72 occupants sustained a total of 89 AIS2+ thoracolumbar (TL) spine fractures. For 70 of the fractures (53 occupants), information on injured vertebrae location is available and is displayed in Fig. 9. The 19 fractures

with unknown vertebra location are distributed between the spine regions as follows: 5 Th1-Th6; 9 Th7-12; and 5 L1-L5.

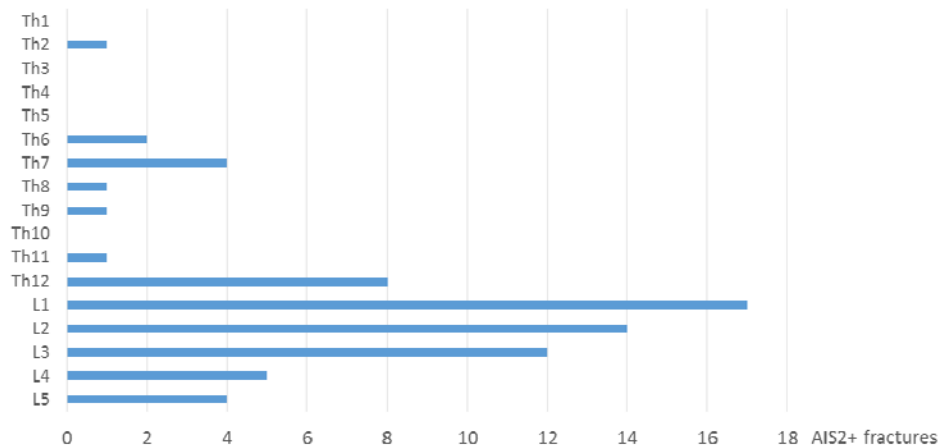


Fig. 9. Numbers of AIS2+ fractures for the 53 cases in the in-depth data subset, with detailed fracture information per thoracic (Th1-12) and lumbar (L1-5) vertebrae.

The majority of the fractures are seen in the lumbar region, with the most frequently injured vertebra being L1 (Fig. 9). The vertebrae closest to the transition between the thoracic and lumbar region of the spine are those most frequently injured. In addition, an area at mid-thoracic spine is identified as well (Fig. 9). The occupant sustaining an AIS2 transverse process fracture at Th2 was a right-side, rear-seat occupant exposed to a frontal impact into a tree after running off the road. He had most likely slipped out of the shoulder portion of the belt.

In total, 13 occupants sustained multiple AIS2+ TL fractures: nine double and four triple. For all except two, the fractures are positioned at adjacent vertebrae. The two exemptions sustained two fractured vertebrae in mid-thorax together with a fractured lumbar vertebra (L2 and L3, respectively). One of them was a driver and the other one a rear-seat passenger, and both were exposed to multiple impacts with a significant influence of Rear *direction-of-impact*.

Among the 72 occupants with AIS2+ TL fractures, only 25% sustained AIS2+ injuries to the chest, abdomen or pelvis. This means that for the majority of the occupants, the TL fractures were the only serious injuries in the torso-pelvis region. In total, 42 occupants (58%) had no other AIS2+ injury than the injuries to the TL spine.

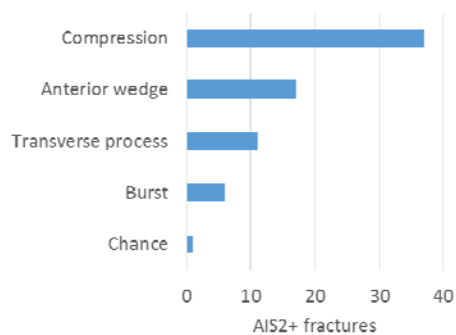


Fig. 10(a). Numbers of AIS2+ fractures, per type of fracture, for the 54 cases in the in-depth data subset with detailed fracture information.

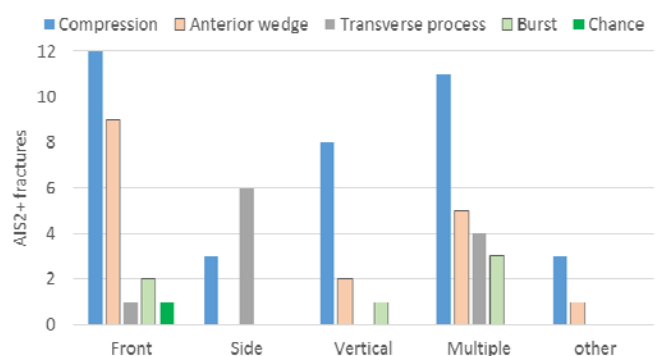


Fig. 10(b). Numbers of AIS2+ fractures, per type of fracture, separated by *direction-of-impact*.

Figures 10(a) and (b) show the distribution of different fracture types: overall (Fig. 10(a)) and separated by *direction-of-impact* (Fig. 10(b)). Five different fracture types are seen among the cases in the in-depth data subset. Compression fractures account for 51%, followed by anterior wedge fractures at 24%, transverse

processes fractures at 15% and burst fracture at 8%. In addition, one driver exposed to an under-ride type of frontal impact to the side of a truck sustained a chance fracture.

As can be seen in Fig. 10(b), compression fractures are mainly found in Front and Vertical *direction-of-impact*, as well as within the group of Multiple *direction-of-impact*. The anterior wedge fracture type is also associated with the impacts to the Front and Vertical *direction-of-impact*, as well as Multiple *direction-of-impact*. For Side *direction-of-impact*, the transverse process fractures are most commonly seen. Twenty fractures are not included in Fig. 10(a) and (b) due to lack of information of fracture type. These cases are distributed according to *direction-of-impact* as follows: six Front; four Side; one Vertical; and nine Multiple.

Case descriptions, examples

Three cases have been selected to illustrate examples of the most common fracture type, i.e. compression fracture. The cases were chosen to provide insight into the differences in accident type, although the injury fracture type is similar in all cases.

In **Case 1**, a restrained male driver aged 40 was driving his Volvo S80 (year model 2000) on a rural road with speed limit of 90 km/h. It was daytime, and the road was partially slippery due to ice. Suddenly, a deer appeared on the road. He tried to steer out of the collision path, but lost control of the car and ran off the road to the right and into a ditch, followed the ditch and ran into an embankment of a crossing road. Due to the interaction with the sloping embankment, the vehicle got into a turnover and ended up on its right side. Main interactions are seen at the undercarriage (Fig. 11). The driver sustained an AIS2 compression fracture on the L1 vertebra. In addition, he sustained pain in the chest, right knee and right elbow and a contusion on his nose (all of AIS1). The mechanism behind the lumbar spine fracture is likely axial loads, most probably occurring when impacting the embankment.



Fig. 11. Vehicle in Case 1, run-off-road crash.



Fig. 12(a). Exterior view of vehicle in Case 2, side impact.



Fig. 12(b). Interior view of driver seat in Case 2.

In **Case 2**, a restrained male driver aged 19 was driving a V70 (year model 2011) on a slippery rural road early in the morning in winter darkness. Usually he drove another car, but it was at the workshop on this particular day. The speed limit of the road was 80 km/h. The driver was in a hurry because he was late for an appointment. He approached two cars, which were driving slowly, and decided to overtake these cars. When doing that, he failed to steer back into lane. Instead, the car began skidding, exposing the left side towards opposing traffic. At that time a KIA Ceed was approaching in the opposite lane. The KIA impacts frontally into the Volvo's driver door area with an angle slightly forward. During the crash, the SIPSbag (torsobag), the Inflatable Curtain and the torso and lap-belt pretensioners activate in the Volvo car. The maximum residual interior intrusions laterally in the area of the seat cushion are 29 cm (rear) and 35 cm (front), respectively. The Volvo driver was taken to hospital, where he remained in intensive care for a week. He sustained an AIS2 compression fracture on the L4 vertebra, which was most displaced in its left ventral part. In addition, he sustained an AIS3 splenic rupture, AIS2 pelvic fractures, a left transverse process fracture on L3 (AIS2), sprain in the left shoulder (AIS1) and concussion with loss of consciousness (AIS2). The mechanism behind the compression lumbar spine fracture is likely axial loads while bending forward slightly to the left, caused by an upward shift of the seat during the intrusion in combination with the lap-belt-pelvis interaction during the ride-down. This hypothesis is supported by the ramus inferior os pubis fractures, which most likely result from loads transmitted in a direct oblique impact upwards-inwards from stiff structures of the left part of the seat, caused

by the intruding structure (Fig. 12(b)).

The restrained 44-year-old male driver in **Case 3** was driving a Volvo V40 (2014) on a wet, rural road during the evening, in darkness (Fig. 13(a)). He was driving at approximately 80 km/h when an opposing car, for unknown reason, drifted into his lane (Fig. 13(b)). The driver of the Volvo applied the brakes and reduced the speed by approximately 20 km/h before being impacted by a Peugeot Bipper. The estimated impact speed is 60 km/h (Volvo) and 80 km/h (Peugeot) at approximately 10 degrees and an overlap of 80%. The Volvo driver sustained an AIS2 compression fracture on the L5 vertebra, reduced to approximately 50% of total height (Fig. 13(c)). He was treated with an orthoses. In addition, he sustained a fracture (AIS2) on his right ankle and fractures (AIS2) on the left foot's distal metatarsals 3 and 4, as well as pain (AIS1) in his left thumb. He sustained no injuries to his head or torso. When inspecting the driver seat, deformations on the seat chassis structure, slightly in front of his initial pelvis position, were seen. Although the forces on the vehicle were primarily longitudinal, it is likely that the mechanism behind the lumbar compression spine fracture is axial loads. These are believed to be caused by the pelvis interaction with the seat in combination with the seatbelt interaction.



Fig. 13(a). Vehicle in Case 3, frontal impact.



Fig. 13(b). Accident site in Case 3. The long arrow indicated the position and direction of the case vehicle.



Fig. 13(c). L5 compression fracture in Case 3.

IV. DISCUSSION

Although generally not life threatening, AIS2+ thoracic and lumbar spine injuries are important with respect to long term consequences [20], and the injury rate has only decreased to a small extent in the past decade [2][6]. This study offers a general, as well as a specific, picture of the occurrence of different AIS2+ thoracolumbar (TL) spine injuries in car crashes, categorised by different fracture types and loading direction onto the car during the crash sequence (*direction-of-impact*).

The data used are limited to accidents in Sweden. In addition, the data are restricted to a narrow type of car model. Although these limitations influence the generalisability of the findings, they are also an advantage for studies of injury occurrence, in that they reduce the influence of several factors. In addition, the quality of the in-depth investigations is likely higher, since they are performed by experts on the car models involved. For the purpose of providing state-of-the-art relevant results, the model years are chosen to represent modern cars with high overall safety level. For the same reason, only restrained occupants are included in the analysis.

The two-part studies complement each other. The statistical analysis of the larger statistical subset provides distribution data and shows influencing factors in a general sense. While the closer analysis and categorization of a subset of the AIS2+ TL spine injured occupants generates a better understanding with respect to fracture types and direction of exterior loadings to the car during the event. However, in order to establish injury-causing mechanisms, very detailed data are required. For some of the cases (as exemplified by the three case descriptions above), the cars were available for in-depth investigations and the radiological data were reviewed in collaboration with medical experts. In such cases, the likely injury-causing mechanisms could be established thanks to the exact information of the fracture shape, together with vehicle deformation evidences. However, it was also obvious that without this detailed data, any statements on exact injury-causing mechanisms should be interpreted carefully.

The classification *direction-of-impact* is a result of case-by-case analysis with the aim of providing a good understanding of the loads onto the car. It is estimated based on the residual deformations of the car and the accident scenario description gathered by questionnaire, and also on police reports, when available. This classification adds some additional information as compared to the general classification of accident types.

The results of this study show that there is a relative over-representation of complex events such as multiple impacts and multiple events, including run-off-road among the occupants sustaining AIS2+ TL spine injuries. However, as for the overall MAIS2+ injured occupants, the majority of the AIS2+ spine injured occupants were exposed to frontal impacts. The main reason for this is level of exposure, arising from the fact that frontal impacts are the most frequent accident type. A tendency for heavier and taller vehicle occupants to sustain this type of injury was also seen. This coincided with a relatively higher rate for men as compared to women regarding AIS2+ TL spine fractures. Further investigations are needed to understand if there are injury mechanism-related reasons for this, or if it simply reflects a biased collection due to higher exposure of men in combination with men being physically bigger. Occupant position/posture and degree of spine flexion at impact were seen to influence injury outcome in several cases, which is in line with prior studies [2].

The majority (64%) of the injuries were reported as lumbar spine injuries (L1-L5), while 26% and 10% were located in the lower thoracic spine (Th7-Th12) and upper thoracic spine (Th1-Th6), respectively. Although the fractures are distributed over most of the thoracic and lumbar spine, the vertebrae closest to the transition between the lumbar and thoracic segment of the spine are those most frequently injured. These results confirm prior studies [2][4][11]. In addition, an area at mid thoracic spine was identified as well (Fig. 9). The situations resulting in these fractures were of varied character, but they exhibit some similarities in interaction between upper torso and head and/or major pre-crash kinematics posing the occupants into a non-optimal restraint position. These types of fracture are not unique to this group, but it does seem relatively more pronounced than the occupant sustaining fractures further down the spine. It would be interesting to explore this further, in order to gain an understanding of the differences in injury mechanisms.

The character of the AIS2+ TL spine fracture types, together with the situations of occurrence, provide insights into potential occupant loading mechanisms in relation to different restraint interaction mechanisms. After compression fractures, the next most common types are anterior wedge fractures and transverse process fractures. In this study, anterior wedge fractures are mainly seen in frontal and multiple impact or events. The relevant cases indicate a bending of the thoracolumbar column with high vertical loads, which gives the characteristics of the wedge fracture. Transverse processes fractures are highly associated with excessive lateral movement of the occupant and are typically observed in side and multiple impacts, as exemplified in case 2.

Compression fracture is the most common fracture type in this study, confirming prior studies [2]. Although likely similar in its injury mechanism (compression force), it occurs in several different accident types. The driver in case 2 illustrates an interesting case of compression fracture occurring in a pure side impact. During the in-depth investigation of the car after the crash, it could be seen that the driver seat's left side had been forced into an upward motion by the intruding side structure (Fig. 12(b)). This interaction corresponded to the character of the fracture, confirming this to be a likely mechanism in this specific case. This case illustrates the importance of understanding the occupant's interaction to seat, side structure and restraints. Real-world data provides an important source for this, and an understanding of the occupant loading mechanisms helps to guide developments of countermeasures and methods of evaluation.

Less than 30% among the TL spine injured also sustained AIS2+ injuries to the thorax, abdomen or pelvis; cases 1 and 3 are both examples of this. Overall, in more than half of the in-depth cases, the injuries to the TL spine were the only AIS2+ injuries sustained by the occupant. This is most likely a result of the fact that overall vehicle safety has improved significantly and that there has not been enough focus on TL spine fractures in car crashes. The present study shows that AIS2+ TL spine fracture occurs in all different types of accident situation. The more complex events are relatively over-represented. This, of course, makes it more difficult to address these issues, since most likely several parallel efforts would be needed to reach an overall reduction. Some few references [2][12] have studied the general distribution of TL spine injuries, but the majority have addressed certain crash situations; eg frontal crashes [4][8-11] or side impacts [13]. More real-world data studies such as this, addressing all accident types together, would help to establish whether there are any general principles of improvement that could facilitate an efficient identification of suitable countermeasures.

Vertical occupant loading was addressed by [18], proposing a test set-up as well as a modified vehicle seat

addressing reduced occupant vertical acceleration, such as that typically occurring in case 1 of this study. Together with sensing and occupant retention functionalities, the seat was included in a run-off-road protection package that was put in production in 2015 [21], with the target of reducing the occurrence of vertical load-induced TL fractures.

Based on the present study, it is clear that AIS2+ TL fractures in Front *direction-of-impact* type of loadings need more attention. Although occurring in numerous ways, a typical situation is the high severity pure frontal impact, as illustrated in case 3. The crash severity is typically high, with a large front structure engagement exerting the occupant for high accelerations. The uninjured head and chest of the driver in case 3, provide evidence of an overall good protection and ride-down performance. The deformations in the seat structure showed evidence of high vertical loading, which most likely occurred while the occupant's pelvis was kept back by the seatbelt and knee airbag. Improved understanding of influencing factors and timing of occurrences in cases like this, as well as other situations, means that the various injury mechanisms can be better understood and protective measures can be developed. Thoracolumbar spine-related mechanisms in frontal impacts have been discussed by several authors [4][9][11][22]. Some of them examine these mechanisms in the context of submarining and the corresponding occurrence of injuries to the abdomen and pelvis. In this study, there was no corresponding occurrence of submarining nor injuries to the abdomen and pelvis in frontal impact situations. Instead, as case 3 illustrates, the overall severity of the crash together with the seat and seatbelt interaction are the main factors to consider, at least for the safe modern vehicles as included in this study.

Injuries to the thoracolumbar spine need more attention, too. Test methods and established injury criteria for evaluating risk of these injuries are needed. In particular, there is a need to evaluate and further develop the human substitutes in testing, such as crash test dummies and virtual human body models. Real-world data provide an important source for understanding the vehicle and occupant loading mechanisms causing the different AIS2+ TL spine fractures. The results of this study can hopefully help guide the development of test methods and countermeasures addressing thoracolumbar spine injuries in car crashes.

V. CONCLUSIONS

The spine is in the top three most frequently injured body regions with respect to MAIS2+ injury rates per body region, in this dataset of modern passenger cars. The vast majority (74%) of the spine-injured occupants sustained fractures to the thoracolumbar (TL) spine. Relative to overall MAIS2+ distribution, the AIS2+ TL injured occupants are over-represented in multiple and complex events (including run-off-road), while the opposite is seen in pure frontal, side and rear-end impacts. Nevertheless, the AIS2+ TL injured occupants are mainly seen in pure frontal impacts (36%), followed by multiple impacts (24%).

The 72 cases available for in-depth data analysis, and for which the *direction-of-impact* was established, provided enhanced insight into the car's main force of interaction during the crash. Front *direction-of-impact* was found to be the most frequent category, followed by vertical *direction-of-impact*. In several of the cases, multiple *direction-of-impacts* occurred. Influential characteristics of the front *direction-of-impact* cases are large front structure engagement together with rather extensive deformation, exerting the occupants for high accelerations. One case illustrating this is described. A typical vertical *direction-of-impact* is a run-off-road event with interaction with the undercarriage, exemplified by another case description.

Most of the AIS2+ TL fractures are found in the area of transition between the thoracic and lumbar spine. The majority of the fractures are compression fractures, followed by anterior wedge fractures and transverse process fractures. The compression fractures occur mainly in cases that feature pure front, pure vertical or multiple *direction-of-impact* loads to the car.

Real-world data provide an important source for understanding the vehicle and occupant loading mechanisms causing the different AIS2+ TL spine fractures. This information is important when addressing the development of methods, tools and criteria, as well as countermeasures.

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