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Cervical vertebral and spinal cord injuries in rollover occupants

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Abstract

Background Rollover crashes continue to be a substantial public health issue in North America. Previous research has shown that the cervical spine is the most injured spine segment in rollovers, but much of the past research has focused on risk factors rather than the actual cervical spine injuries. We sought to examine how different types of cervical spine injuries (vertebral and/or cord injury) vary with different occupant-related factors in rollovers and to compare these with non-rollovers.

Methods We obtained crash and injury information from the National Automotive Sampling System–Crashworthiness Data System (NASS-CDS) for 2005–2015 and Crash Investigation Sampling System (CISS) for 2017–2022. Based on weighted data, we calculated relative risks to assess how occupant sex, seat belt use, ejection status, and fatal outcome relate to the rate of different cervical spine injuries in rollovers and non-rollovers.

Results In NASS-CDS occupants with cervical spine injuries ($N = 111,040$ weighted cases), about 91.5% experienced at least one vertebral injury whereas only 11.3% experienced a spinal cord injury (most of which had a concomitant vertebral fracture). All types of cervical spine injuries we examined were 3.4–5.2 times more likely to occur in rollovers compared to non-rollovers. These relative risks were similar for both sexes, belted and unbelted, non-ejected, and non-fatal occupants. The number of weighted CISS occupants with cervical spine injuries ($N = 42,003$) was smaller than in the NASS analysis, but cervical spine injuries remained 6.25 to 6.36 times more likely in rollovers compared to non-rollovers despite a more modern vehicle fleet.

Conclusions These findings underscore the continued need for rollover-specific safety countermeasures, especially those focused on cervical spine injury prevention, and elucidate the frequency, severity and other characteristics of the specific vertebral and spinal cord injuries being sustained in rollovers. Our findings suggest that countermeasures focused on preventing cervical vertebral fractures will also effectively prevent most cervical spinal cord injuries.

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Background

Motor vehicle rollover crashes remain a public health concern in North America and elsewhere in the world despite improvements in vehicle stability and passive safety. In the United States, rollovers account for only 2% of all motor-vehicle crashes yet cause almost a third of all vehicle-related fatalities (National Center for Statistics and Analysis 2020). Rollovers also cause many non-fatal cervical spine fractures, dislocations, and spinal cord injuries, some of which are catastrophically life-altering for the injured individuals and include tetraplegia and ventilator dependence. The mechanism of many of these injuries has been shown in rollover tests with anthropomorphic tests devices (ATDs) where the ATDs sustain headfirst impacts with the vehicle's roof, during roof-to-ground impacts while the rolling vehicle is inverted (Bahling et al. 1990; Cooper et al. 1997; Moffatt et al. 2003; Raddin et al. 2009). These injuries to the cervical spine create sizeable societal burdens on national economies and healthcare systems (Berkowitz 1998; Burns et al. 2010; Digges 2002; Ma et al. 2014; National Spinal Cord Injury Statistical Center 2020). Although the magnitude of the societal and health care problems caused by cervical spine injuries in automotive rollovers is understood, there is a paucity of information on the rates and characteristics of different cervical spine injuries in rollover crashes. In order to prevent these injuries, researchers and manufacturers need to understand the injury mechanisms responsible. This information is of primary importance to enable prevention of future cervical spine injuries in rollover crashes.

Considerable epidemiological data exist describing injury characteristics in rollover occupants (Bose et al. 2011; Fakharian et al. 2017; Foster et al. 2012; Funk et al. 2012; Ivarsson et al. 2015; Mandell et al. 2010; McMurry et al. 2016; Parenteau and Viano 2014; Ridella and Eigen 2008; Stein et al. 2011). The occurrence and severity of various injuries in rollovers have been associated with seating position (Funk et al. 2012; Jehle et al. 2007; Viano et al. 2007), occupant age (Bilston et al. 2011; McMurry et al. 2016; Stein et al. 2011), ejection status (Funk et al. 2012; Gloeckner et al. 2006), and seatbelt use (Funk et al. 2012; Moore, 2005; Parker, 2007; Viano et al. 2007), but none of these studies focused specifically on cervical spine injuries in rollover crashes. Parenteau and Viano (2014) examined injury severity (using the Abbreviated Injury Scale, AIS) along the entire spine and found that occupants in rollovers had the highest rate of AIS4+cord injuries and AIS3 fracture-dislocations compared to other collision types. They also noted that 69.5% of all AIS4+spinal cord injuries in rollovers were to the cervical spine, but did not explore further the types and characteristics of cervical spine injuries in rollover crashes. Stein et al. (2011) found that vertebral column fractures and spinal cord injuries in the cervical spine were 5.3 to 6.5 times more likely in rollover crashes than in frontal crashes. These authors reported no differences in the crash characteristics (e.g., crash type, seat belt use, etc.) or occupant characteristics (e.g., sex, age, etc.) between occupants with cervical spine fractures versus spinal cord injuries, but these findings were based on only 57 occupants who experienced rollovers amongst the 407 occupants with cervical spine injuries in the CIREN[1] database at the time. To our knowledge, an analysis of population-weighted data that distinguishes between spinal cord injuries with and without fractures, as well as vertebral fractures that occur with and without cord injuries, has not been reported. Despite Stein et al.'s and Viano et al.'s detailed analyses, the relative frequency and relative risk of different types of cervical spine injuries in rollover and non-rollover crashes remain unexamined.

To address this gap in the literature, the goal of the current study is to examine how the different types and patterns of cervical spine injuries (e.g., vertebral fracture, spinal cord injury, etc.) vary with different occupant-related factors in rollover and (for comparison) non-rollover crashes. More specifically, we sought to determine: (i) the rate of cervical spine injuries in rollover and non-rollover crashes, (ii) how occupant sex, seat belt use, ejection status, and fatal outcome relate to the rates of cervical spine injuries in rollover and non-rollover crashes, and (iii) which types of vertebral injuries are associated with spinal cord injuries in rollover and non-rollover crashes.

Methods

We extracted data from two multi-site US databases: the National Automotive Sampling System – Crashworthiness Data System (NASS-CDS) and its more recent replacement the Crash Investigation Sampling System (CISS) to examine both older and newer vehicles. Because of differences in the databases (Zhang et al. 2019) and our desire to compare the relative risks between an older and newer fleet, we performed separate analyses for each dataset.

NASS-CDS analysis

The NASS-CDS database compiled by the National Highway Traffic Safety Administration (NHTSA) is a probability sample of police-reported tow-away crashes and was used to query real-world crash and injury data for our analysis. Annually, detailed crash and injury data from about 5000 crashes were studied in 24 geographically distributed

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[1] CIREN (Crash Injury Research Engineering Network) is a database by the National Highway Traffic Safety Administration that includes crash investigation data, while providing multidisciplinary analyses of medical and engineering evidence to determine injury causation ("Crash Injury Research | NHTSA," n.d.)

"Primary Sampling Units" (PSUs) across the USA and stored in the publicly available NASS-CDS database. The NASS-CDS provides the raw counts as well as ratio inflation factors that weight the raw data to represent estimates of all police-reported, motor-vehicle, tow-away crashes occurring in the USA in a given year up to 2015 (Radja 2016; Zhang et al. 2019). NASS-CDS data consist of multiple sub-records, which include the accident (ACCIDENT), general vehicle (GV), occupant assessment (OA), occupant injury (OI), vehicle exterior (VE), vehicle interior (VI), and accident event (EVENT) records. To avoid the loss of data rows, these seven sub-records were synthesized in SAS 9.4 (SAS Institute, Cary, NC) for each year using the *PROC SQL* function in the abovementioned order. The complete dataset was created by merging synthesized sub-records for the years 2005–2015 in SAS Enterprise 7.1 (SAS Institute, Cary, NC). For clarity, NASS-CDS variable names are capitalized in the following text.

To select the data used for our NASS-CDS analysis, we first filtered the merged data for criteria related to vehicle and occupant details. Only passenger cars and light trucks (BODYTYPE≤49) with model years of 1985 or newer (MODELYR≥1985) were included in our analysis. Excluding pre-1985 vehicles for crashes only eliminated <1% of vehicles (728 of 84,659 vehicles) and about 1.5% of occupants (1811 of 117,816 occupants). Occupants over 8 years old (AGE>8) and taller than 145 cm (HEIGHT>145) were included. These criteria included 5th percent females (McDowell, 2008), but excluded very short individuals, and were consistent with age and height restrictions for booster seat use (i.e. most occupants shorter than those included would be mandated to use child booster seats) legislated by most states with NASS-CDS PSUs ("State Laws," n.d.; United States Government Accountability Office 2015). Occupants were also excluded if they were using a child restraint of any kind (CHTYPE>0).

The dependent variables for all four of our study goals were the type and combination of cervical spine injuries, which were classified using the 1998 Abbreviated Injury Scale code (AIS98) in the NASS-CDS database (Association for the Advancement of Automotive Medicine 2008). All cervical spine injuries (REGION90=6, STRUSPEC=2) were identified and first categorized into three main groups (Table 1). The first group consisted of occupants with vertebral injuries only (abbreviated VI in Table 1) and was defined by any number of fractures or dislocations to the cervical vertebrae (STRUTYPE=5 and INJLEVEL=04, 06 to 34 inclusive) without any spinal cord involvement (STRUTYPE≠4). The second group consisted of occupants with spinal cord injuries (abbreviated CI in Table 1) and was defined as any number of spinal cord injuries with or without associated fractures or dislocations (STRUTYPE=4, INJLEVEL=00 to 76

inclusive) and without any fractures or dislocations unrelated to the spinal cord injury (STRUTYPE≠5). The third group consisted of occupants who had both a spinal cord injury (STRUTYPE=4, INJLEVEL=00 to 76 inclusive) and a separate, distinct vertebral fracture or dislocation (STRUTYPE=5 and INJLEVEL=04 to 34 inclusive). This third group of vertebral and cord injuries was denoted by the abbreviation VCI in Table 1. Each occupant was included in only one of these three groups. In addition to these three main groups, we also considered combinations of the groups: all occupants with vertebral injuries (All-VI=VI+VCI), all occupants with spinal cord injuries (All-CI=CI+VCI), and all occupants with vertebral and/or spinal cord injuries (ALLINJ=VI+CI+VCI). Occupants with only ligamentous injuries or strains (STRUTYPE=4 and INJLEVEL=84 or 78), intervertebral disc injuries (STRUTYPE=5 and INJLEVEL=00, 02, 03 or 99), and nerve root injuries (STRUTYPE=3), whether isolated or combined, were excluded from all groups to isolate only spinal cord and bony vertebral injuries. Based on these definitions, the AIS values for all VIs varied from AIS2 to AIS3 and all CIs varied from AIS3 to AIS6. All included injuries require physical examination or imaging to be diagnosed.

To achieve our third goal, i.e., how different types of vertebral injuries combine with spinal cord injuries in rollover and non-rollover crashes, we further categorized the occupants with spinal cord injuries (the All-CI group) based on their associated vertebral injuries into the following five subgroups:

no fractures or dislocations
(INJLEVEL=2, 12, 22, 30, 44, 62, 70), fractures
(INJLEVEL=4, 14, 24, 32, 46, 64, 72), dislocations
(INJLEVEL=6, 16, 26, 34, 48, 66, 74), combined fracture-dislocations
(INJLEVEL=8, 18, 28, 36, 50, 68, 76) and not further specified (NFS)
(INJLEVEL=0, 1, 10, 20, 21, 29, 40, 42, 60, 61, 69).

The primary independent variables for our analysis consisted of the collision type (rollover versus non-rollover), seat belt use, ejection status, and fatality status. Vehicles were categorized according to whether they experienced a rollover crash (ROLLOVER=1 to 12 quarter turns) or non-rollover crash (ROLLOVER=0 quarter turns). We discarded rollovers of more than 3 revolutions (ROLLOVER>12 quarter turns), end-over-end rollovers (ROLLOVER=98) due to their rare occurrence (<1% of NASS and CISS cases) and substantially different kinematics, and any crashes coded as unknown (ROLLOVER=blank; 65 vehicles, 99 occupants). Occupants were categorized as belted if they used a manual lap and shoulder belt (MANUSE=4) or an automatic belt system (ABELTUSE=1), and

Table 1 Summary of the three main groups of cervical spine injuries. Subscripts i and j denote different AIS-coded injuries within the same individual's cervical spine

Group	Description of cervical spine injury	Conditions
VI	Vertebral injury only - One or more fractures or dislocations with no spinal cord injury	$(STRUTYPE_i=5)$ & $(INJLEVEL_i=04$ to $34)$ & $(STRUTYPE_j \neq 4)$
CI	Spinal cord injury - One or more spinal cord injuries with or without associated fracture or dislocation; no other vertebral injury without spinal cord injury	$(STRUTYPE_i=4)$ & $(INJLEVEL_i=00$ to $76)$ & $(STRUTYPE_j \neq 5)$
VCI	One or more spinal cord injuries with or without fracture or dislocation PLUS one or more fractures or dislocations with no spinal cord injury	$(STRUTYPE_i=5)$ & $(INJLEVEL_i=04$ to $34)$ & $(STRUTYPE_j=4)$ & $(INJLEVEL_j=00$ to $76)$

categorized as unbelted otherwise. We discarded occupants missing both MANUSE and ABELTUSE data. Occupants were classified as ejected (EJECTION=1) or not ejected (EJECTION=0), and were discarded otherwise. Occupants were only categorized as being fatally injured when TREATMNT=1. For the latter three independent variables, i.e., seat belt use, ejection status or fatality status, we excluded occupants on an analysis-by-analysis basis. For example, an occupant with missing seat belt data was only excluded from the seatbelt analysis.

We also conducted a separate sub-analysis wherein we attempted to select occupants who likely sustained their cervical spine injury inside the vehicle during the rollover portion of the crash. This has been done previously (Bose et al. 2011; Funk et al. 2012; McMurry et al. 2016). For this sub-analysis, we only included occupants in rollovers who met all of the following additional criteria: (i) the first or second most severe crash event was the rollover (OBJCONT1=31 or OBJCONT2=31), (ii) the rollover was not an end-over-end rollover (ROLINDIR≠8 or blank, or OBJCONT≠32), (iii) at least half a roll occurred (ROLLOVER≥2), (iv) a collision with another vehicle did not initiate the rollover (ROLINTYP≠7), and (v) the occupant was not completely ejected (EJECTION≠1). Occupants who were partially ejected (EJECTION=2) were only included if their cervical spine injury was caused by sources within the vehicle (INJSOU<451 or INJSOU=570, 572, 575, 576, or 602).

CISS analysis

We repeated the foregoing analyses using the CISS database to evaluate the impact of advancements in the field of passive safety over the last decade and derive conclusions more relevant to the current vehicle fleet. CISS is NHTSA's newer database of nationally collected surveys of police-reported vehicle crashes (Radja et al. 2023; Zhang et al. 2019) and, compared to NASS-CDS, prioritizes the selection of newer vehicles (≤4 years old) that are more likely to be equipped with advanced crashworthiness and crash-avoidance technologies (Mynatt and Brophy 2017). We combined CISS data files from 2017 to 2022 and excluded data from the 2016 pilot year. Similar to our NASS-CDS analysis, we filtered the merged data for vehicle type (BODYTYPE≤49), occupant age (AGE>8), occupant

height (HEIGHT>145), and excluded child restraint use (CHTYPE>0). Only vehicle model years 2010 and newer (MODELYR≥2010) were included, as these vehicles will likely include advancements in rollover safety due to introduced safety legislation, e.g. relating to roof strength (FMVSS No. 216a, 2009) and ejection mitigation (FMVSS No. 226, 2011).

Since the CISS dataset was smaller than the NASS-CDS dataset and some of the injury categories contained only a few raw cases (e.g., there were only 5 raw VCI cases), we focused our CISS analysis on the All-VI, All-CI, and All-Injuries groups. Occupant injuries in CISS are described using the 2015 AIS code (AIS15, The Association for Advancement of Automotive Medicine 2016), which required slightly different definitions for our injury groups. For our CISS analysis, vertebral injury (VI) was defined by any number of fractures or dislocations to the cervical vertebrae (STRUTYPE=5 and INJLEVEL=04, 06 to 40 inclusive) without spinal cord involvement (STRUTYPE≠1) and cord injury (CI) was defined as any number of spinal cord injuries with or without associated fractures or dislocations (STRUTYPE=1, INJLEVEL=00 to 36 inclusive) and without any fractures or dislocations unrelated to the spinal cord injury (STRUTYPE≠5). Both the All-VI and All-CI groups contained the 5 occupants who had both a VI and CI. Duplicate occupants were removed before the analyses.

We analyzed the same independent variables we used in the NASS-CDS analysis, but adjusted some definitions to accommodate CISS's revised variable structure: both seat belt use (BELTUSE=4) and fatality (MORTALITY=1) were redefined. Since the analyses only encompassed vehicles manufactured after 2010, the infrequent instances of a distinct lap-(BELTUSE=3) and shoulder belt (BELTUSE=2) were negligible in terms of statistical strength and allowed us to control for one seatbelt type. For our analysis of how different types of vertebral injuries combined with spinal cord injuries (All-CI group) in both rollover and non-rollover crashes, our definitions underwent the following AIS15-related changes: no fractures or dislocations (INJLEVEL=2,12,22,30), fractures (INJLEVEL=4,14,24,32), dislocations (INJLEVEL=6,16,26,34), combined fracture-dislocations (INJLEVEL=8,18,28,36) and not further specified (NFS) (INJLEVEL=0,1,10,20,21,29). To filter for occupants who likely sustained their cervical spine injury inside

the vehicle during the rollover portion of the crash, we also performed a sub-analysis where we only included occupants who, similar to the equivalent NASS-CDS analysis, met all of the following additional criteria: (i) the first or second most severe crash event was the rollover (OBJCONT=31 and DVRANK=1 or 2), (ii) the rollover was not an end-over-end rollover (ROLLTYPE=1), (iii) at least half a roll occurred (ROLLTURN≥2), (iv) a collision with another vehicle did not initiate the rollover (1≤ROLLINITYP≤6), and (v) the occupant was not completely ejected (EJECTTYPE≠1). Occupants who were partially ejected (EJECTTYPE=2) were only included if their cervical spine injury was caused by sources within the vehicle (IPC1<1100 or 1501≤IPC1≤1698).

Statistical analysis

All descriptive statistical analyses were performed in SAS 9.4 (SAS Institute, Cary, NC) using the SAS *SURVEYFREQ* procedures for analyzing complex sample surveys. We used the default variance estimation method, i.e., a Taylor series approximation. We calculated population totals (weighted data), as well as population proportions and relative risks for 2×2 frequency tables from the weighted data for each injury category. We also calculated the 95th percentile confidence intervals for population totals, proportions, and relative risks. In NASS-CDS, from 2002 to 2007, three extra so-called alliance PSUs were deleted and the weighting factors for the remaining PSUs were adjusted. Relative risks (RR, Eq. 1) and their confidence intervals were calculated in SAS, and used to compare rollover and non-rollover risks for each cervical spine injury category. Relative risks were considered significant

if the 95th -percentile confidence interval (CI) did not include 1. Relative risks between independent subgroups (e.g., males and females), and relative risks in NASS-CDS and CISS were compared using a test of interaction at a significance level of α≤0.05 (Altman and Bland 2003).

$$
RR = \frac{\left(\frac{N_{rollover}^{injured}}{N_{rollover}^{all}}\right)}{\left(\frac{N_{nonrollover}^{injured}}{N_{nonrollover}^{all}}\right)} \tag{1}
$$

Results

NASS-CDS analysis

Of all occupants included in our NASS-CDS analysis, 7.3% (1.685 M/23.204 M) or 153,169/year experienced a rollover crash and about 0.5% of all occupants (0.111 M/23.204 M) or 10,095/year experienced a cervical spine injury (Table 2). Amongst all occupants with cervical spine injuries, about 91.5% (101.7k/111.0k) experienced at least one vertebral injury, whereas only 11.3% (12.6k/111.0k) experienced a spinal cord injury. Both of these proportions were similar for rollover occupants (93.7% and 9.1%, respectively) and non-rollover occupants (90.7% and 12.2%, respectively).

Although most cervical spine injuries occurred in non-rollover crashes (Table 2b), proportionally more cervical spine injuries occurred in rollover crashes than in non-rollover crashes. Despite rollovers accounting for only 7.2–7.4% of occupant exposures (Table 3a), between 21.0% (14.4–27.6%) of cervical cord injuries (CI) and 28.8% (20.1–37.4%) (mean and 95th percentile

Table 2 Summary of the (a) raw counts and (b) weighted data for the three primary injury categories (top three rows of each table), the three combined injury categories (middle three rows), and all exposed occupants (bottom row). Also shown are the 95th percentile confidence intervals (CI) for the weighted data

a) Raw counts

Injury Category	Rollover	Non-Rollover	Total
VI - Vertebral Injuries only	368	800	1168
CI – Cord injuries	39	153	192
VCI – Separate VI and CI	16	24	40
All-VI (VI+VCI)	384	824	1208
All-CI (CI+VCI)	55	177	232
All-Injuries (VI+CI+VCI)	423	977	1400
All Exposed Occupants	5,776	45,884	51,660

b) Weighted data

Injury Category	Rollover	(95th CI)	Non-Rollover	(95th CI)	Total	(95th CI)
VI - Vertebral Injuries only	28,377	(14,559−42,195)	70,062	(48,975−91,148)	98,439	(68,069−128,808)
CI – Cord injuries	1,975	(661−3,288)	7,412	(3,435−11,389)	9,387	(4,296−14,477)
VCI – Separate VI and CI	885	(0−1,888)	2,330	(0−5,180)	3,215	(262−6,167)
All-VI (VI+VCI)	29,262	(15,080−43,443)	72,392	(51,334−93,450)	101,653	(70,927−132,380)
All-CI (CI+VCI)	2,859	(871−4,848)	9,742	(4,997−14,487)	12,601	(6,909−18,293)
All-Injuries (VI+CI+VCI)	31,236	(15,839−46,633)	79,804	(57,078−102,530)	111,040	(76,466−145,614)
All Exposed Occupants	1,684,859	(1,165,772−2,203,947)	21,519,968	(15,312,915−27,727,022)	23,204,828	(16,533,414−29,876,242)

Table 3 Weighted counts and proportions (%) for (a) all exposed occupants (injured and uninjured) and (b) all injured occupants (occupants with cervical spine injuries) separated by their exposure to a rollover or non-rollover crash. Separate analyses are tabulated for cases where sex, seatbelt use, ejection status and fatality information was known. Abbreviations: R = rollover, NR = non-rollover, N = weighted counts, Nall = total weighted counts for each condition. The percentages for the rollover (R/N) and non-rollover (NR/N) conditions for each row sum to 100%, whereas the total column percentages (N/Nall) for each group sum to 100%

a) All Exposed Occupants

Group	Rollover		Non-Rollover		Total	
	R	R/N	NR	NR/N	N	N/Nall
Sex						
Female	641,371	5.6%	10,769,883	94.4%	11,411,253	49.2%
Male	1,043,477	8.9%	10,746,176	91.1%	11,789,653	50.8%
Total	1,684,848	7.3%	21,516,059	92.7%	23,200,906	100.0%
Seat belt use						
Belted	1,327,539	6.8%	18,210,771	93.2%	19,538,310	91.6%
Unbelted	253,601	14.1%	1,545,673	85.9%	1,799,274	8.4%
Total	1,581,140	7.4%	19,756,444	92.6%	21,337,584	100.0%
Ejection						
Ejected	88,119	67.5%	42,521	32.5%	130,640	0.6%
Not Ejected	1,591,485	6.9%	21,448,651	93.1%	23,040,136	99.4%
Total	1,679,604	7.2%	21,491,172	92.8%	23,170,776	100.0%
Fatality						
Fatal	31,687	29.6%	75,258	70.4%	106,945	0.5%
Not Fatal	1,653,172	7.2%	21,444,711	92.8%	23,097,883	99.5%
Total	1,684,859	7.3%	21,519,969	92.7%	23,204,828	100.0%

b) Injured Occupants Only

Group	Rollover		Non-Rollover		Total	
	R	R/N	NR	NR/N	N	N/Nall
Sex						
Female	12,727	24.2%	39,893	75.8%	52,620	47.4%
Male	18,509	31.7%	39,911	68.3%	58,420	52.6%
Total	31,236	28.1%	79,804	71.9%	111,040	100.0%
Seat belt use						
Belted	12,619	21.8%	45,243	78.2%	57,863	65.2%
Unbelted	13,499	43.7%	17,421	56.3%	30,920	34.8%
Total	26,118	29.4%	62,664	70.6%	88,783	100.0%
Ejection						
Ejected	9,963	57.6%	7,338	42.4%	17,300	15.7%
Not Ejected	21,078	22.6%	72,139	77.4%	93,218	84.3%
Total	31,041	28.1%	79,477	71.9%	110,518	100.0%
Fatality						
Fatal	5,724	22.6%	19,597	77.4%	25,321	22.8%
Not Fatal	25,512	29.8%	60,207	70.2%	85,719	77.2%
Total	31,236	28.1%	79,804	71.9%	111,040	100.0%

confidence interval) of all cervical vertebral injuries (All-VI) occurred in rollover crashes (Table 4a). This general pattern was observed separately in the female and male subpopulations, the belted and unbelted subpopulations, and in the non-ejected and non-fatal subpopulations (compare the rollover percentages in Tables 3a and 3b). It was not observed in the ejected and fatal subpopulations.

Compared to all occupants involved in non-rollover crashes, the relative risks for the cervical spine injuries in a rollover ranged from 3.40 (2.28–5.09) for occupants with a cord injury (CI group) to 5.17 (3.43–7.81) for

occupants with only a cervical vertebral injury (VI group) (top row of relative risks in Table 4a). These relative risks were significantly greater than 1 for all injury categories, except for occupants with separate vertebral and spinal cord injuries (VCI group), which contained only 40 raw cases (3215 weighted cases) and thus had a large confidence interval (Table 2).

A similar pattern of increased risk for cervical spine injuries in rollover crashes was present in most of the subpopulations we examined (Table 4a). Across the female and male subpopulations, the belted and unbelted

subpopulations, and both the non-ejected and non-fatal subpopulations the relative risks varied from 3.03 (1.75–5.25) to 11.31 (2.13–59.90) (Table 4a). A different pattern was observed, however, in the ejected and fatal subpopulations. In the ejected subpopulation, there was no difference in risk for the injury categories dominated by vertebral injuries (VI, All-VI and All Injuries groups), whereas the cord-related injury categories (CI, VCI and All-CI groups) had a lower risk of injury in rollover crashes compared to non-rollover crashes. The pattern within the fatal subpopulation was less clear, with the VI, VCI and All-VI groups showing no difference in risk, and the CI, All-CI and All Injuries groups showing a lower risk of injury in rollover crashes compared to non-rollover crashes.

When we performed a sub-analysis using only non-ejected occupants whose injuries likely occurred inside the rolling vehicle, the proportions of injuries associated with rollovers diminished to between 8.0% (0.1–15.8%) for the CI group and 16.7% (10.3–23.1%) for the VI group, and only the VI, All-VI and All-Injuries groups had relative risks significantly greater than 1 (Table 4b). The other three injury categories had relative risks that were not significantly different from 1.
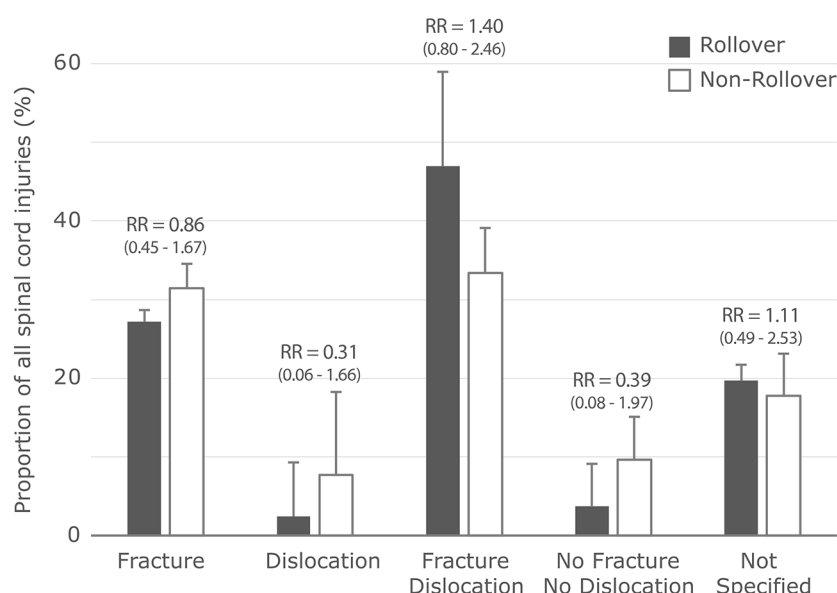
Of the 2859 cervical spinal cord injuries in rollover crashes, 2188 (77%) had an associated vertebral fracture, dislocation, or fracture/dislocation. This proportion was not significantly different from the rate of cervical fractures and/or dislocations associated with spinal cord injuries in non-rollover crashes (7072/9742 = 73%). Within each type of associated vertebral injury, fractures and fracture/dislocations were most common; however, there were no differences in the relative risks for these associated injuries between rollover and non-rollover crashes (Fig. 1).

CISS analysis

Of all occupants in our CISS population, 5.5% (0.386 M/7.068 M) or 64,319/year were involved in a rollover crash and 0.6% (0.042 M/7.068 M) or 7001/year experienced a cervical spine injury (Table 5). Like with the NASS-CDS population, about 92.3% (38.8k/42.0k) of the CISS occupants with cervical spine injuries experienced at least one vertebral injury, whereas only 10.8% (4.5k/42.0k) experienced a spinal cord injury (Table 5). Both proportions were similar for rollover occupants (94.3% and 6.0%, respectively) and non-rollover occupants (91.5 and 12.6%, respectively).

For the remaining analyses, the smaller sample of injured occupants from the CISS dataset (12,196 raw and 7.1 M weighted cases, Table 5) compared to the NASS-CDS dataset (51,660 raw and 23.2 M weighted cases, Table 2) generated wider confidence intervals and rendered fewer comparisons statistically significant. This deficiency in the CISS dataset was most apparent in the cord injury group (All-CI, containing only 27 raw cases, Table 5a), which meant that the All-VI and All-Injuries groups yielded similar results. Nevertheless, like with the NASS-CDS population, the proportion of occupants exposed to rollover crashes (5.3–5.5% for CISS, Table 6a) was lower than the proportion of all cervical spine injuries that occurred in rollover crashes (26.9%,

Fig. 1 NASS-CDS proportions, standard errors, relative risks (RR), and 95th percentile confidence intervals for RR for all cervical spinal cord injuries (All-CI group) in rollovers (dark bars) and non-rollovers (white bars) stratified by the associated vertebral injury mechanisms (x-axis). All relative risks were not significantly different from one

Table 4 (a) Proportions and relative risks for all exposed occupants, and (b) raw counts, weighted counts, proportions and relative risks for occupants whose injuries were likely sustained inside the vehicle. The top table summarizes the proportion (95th percentile confidence interval) of each injury type experienced in rollover crashes (top row) and the relative risk (95th percentile confidence interval) of experiencing each injury type in a rollover crash compared to a non-rollover crash for all occupants (first row of relative risks) and for subgroups of female/male, belted/unbelted, and ejected/not ejected occupants (bottom pairs of rows of relative risks). The bottom table also includes the raw and weighted counts for the sub-analysis of occupants whose injuries were likely sustained inside the vehicle

a) All Exposed Occupants

Injury Group	VI		CI		VCI		All-VI		All-CI		All-Injuries	
	Vertebral Injuries only		Cord injuries		Separate VI and CI		(VI+VCI)		(CI+VCI)		(VI+CI+VCI)	
Proportion in rollover (%)	28.8%	(20.0–37.6)	21.0%	(14.4–27.6)	27.5%	(5.8–58.3)	28.8%	(20.1–37.4)	22.7%	(10.2–35.2)	28.1%	(20.4–35.9)
Relative Risks												
All Occupants	5.17	(3.43–7.81)	3.40	(2.28–5.09)	4.85	(0.86–27.35)	5.16	(3.44–7.74)	3.75	(1.82–7.74)	5.00	(3.46–7.23)
Females	5.52	(2.38–12.80)	3.69	(1.57–8.64)	2.24	(0.32–15.44)	5.48	(2.37–12.65)	3.47	(1.48–8.13)	5.36	(2.38–12.07)
Males	5.03	(3.71–6.83)	3.03	(1.75–5.25)	4.58	(0.68–30.87)	5.01	(3.63–6.91)	3.47	(1.44–8.35)	4.78	(3.51–6.49)
Belted	3.75	(2.02–6.96)	3.88	(2.33–6.46)	8.56	(1.54–47.73)	3.82	(2.05–7.11)	4.61	(2.16–9.85)	3.83	(2.12–6.91)
Unbelted	4.74	(2.15–10.49)	3.60	(0.99–13.11)	8.15	(0.93–71.38)	4.81	(2.20–10.50)	4.49	(1.43–14.09)	4.72	(2.13–10.48)
Ejected	0.89	(0.53–1.51)*	0.28	(0.09–0.89)*	0.06	(0.01–0.58)*	0.70	(0.40–1.22)*	0.14	(0.03–0.64)*	0.66	(0.38–1.13)*
Not Ejected	3.93	(2.34–6.59)	3.07	(1.88–5.01)	11.31	(2.13–59.90)	4.02	(2.41–6.71)	4.01	(2.02–7.95)	3.94	(2.45–6.33)
Fatal	0.85	(0.66–1.10)*	0.24	(0.12–0.48)*	0.15	(0.02–1.09)*	0.83	(0.64–1.09)*	0.23	(0.12–0.47)*	0.69	(0.54–0.90)*
Not Fatal	5.41	(3.38–8.68)	7.06	(3.71–13.44)	5.77	(0.84–39.47)	5.42	(3.43–8.57)	6.53	(2.29–18.58)	5.50	(3.55–8.52)

b) Occupants Whose Injuries Likely Occurred Inside the Vehicle

Injury Group	VI		CI		VCI		All-VI		All-CI		All-Injuries	
	Vertebral Injuries only		Cord injuries		Separate VI and CI		(VI+VCI)		(CI+VCI)		(VI+CI+VCI)	
Raw counts	147		15		7		154		22		169	
Weighted data	16,417	(7,230−25,603)	747	(58−1,384)	549	(0−1,384)	16,965	(7,509−26,422)	1,296	(0−2,620)	17,712	(8,044−27,380)
Proportion in rollover (%)	16.7%	(10.3−23.1)	8.0%	(0.1−15.8)	17.1%	(0.0−45.9)	16.7%	(10.3−23.1)	10.3%	(0.0−21.3)	16.0%	(10.6−21.3)
Relative Risks												
All Occupants	4.58	(2.87−7.31)	1.98	(0.67−5.82)	4.71	(0.65−34.34)	4.58	(2.86−7.36)	2.62	(0.75−9.12)	4.34	(2.85−6.62)

* Significant difference ($p < 0.05$) between the relative risks of the two subgroups (e.g., fatal vs. not fatal)

Table 5 CISS (2017–2022) summary of the (a) raw counts and (b) weighted data for the three combined injury categories, and all exposed occupants. Also shown are the 95th percentile confidence intervals (CI) for the weighted data

a) Raw counts

Injury Category	Rollover	Non-Rollover	Total
All-VI (VI+VCI)	50	178	228
All-CI (CI+VCI)	8	19	27
All-Injuries (VI+CI+VCI)	57	193	250
All Exposed Occupants	1,099	11,097	12,196

b) Weighted data

Injury Category	Rollover	(95th CI)	Non-Rollover	(95th CI)	Total	(95th CI)
All-VI (VI+VCI)	10,640	(1,533 – 19,747)	28,118	(17,268 – 38,969)	38,758	(28,416 – 49,101)
All-CI (CI+VCI)	679	(0 –1,643)	3,867	(1,567 –6,167)	4,546	(2,075 – 7,018)
All-Injuries (VI+CI+VCI)	11,286	(1,869 – 20,704)	30,717	(19,042–42,393)	42,003	(30,540 – 53,468)
All Exposed Occupants	385,915	(309,940 – 461,891)	6,682,172	(5,358,153–8,006,190)	7,068,087	(5,702,665–8,433,509)

CI: 7.5–46.3% for CISS, Table 7a). Also similar to the NASS-CDS data, the same general pattern was present in all of the subpopulations except for the ejected and fatal subpopulations (compare the rollover percentages in Table 6a and 6b).

Compared to occupants involved in non-rollover crashes, the relative risks from the CISS dataset for cervical spine injuries in rollovers were 6.36 (2.11–19.21) for the All-VI group, 3.04 (0.64–14.41) for the All-CI group, and 6.36 (2.21–18.33) for the All-Injuries group (top row of relative risks in Table 7). This pattern of relative risks was also present in the subpopulations (Table 7), albeit fewer of these relative risks were significantly different from one in the CISS data than in the NASS-CDS data. Like the NASS-CDS analysis, female and male occupants, belted and unbelted occupants, non-ejected occupants, and non-fatally injured occupants in the CISS data were more likely to sustain vertebral injuries (All-VI group) in rollovers than in non-rollovers, and ejected occupants and fatally injured occupants were neither more nor less likely to sustain vertebral injuries in rollovers than in non-rollovers (Table 7). With respect to cord injuries (All-CI group) in the CISS data, the average relative risk resembled the pattern in the NASS-CDS data, but none of the CISS-based relative risks were significantly different from unity (Table 7). The relative risks calculated from the NASS-CDS and CISS data were not significantly different.

Our analysis of how different types of vertebral injuries combine with spinal cord injuries revealed that around 90% (615/697 occupants) of cord injuries in rollover occupants had associated fracture-dislocations (60.9%, 60.3–61.4%) and fractures (29.7%, 29.3–30.2%) (Table S1 in the Supplemental Materials). Due to the paucity of CISS spinal cord injury data (only 27 raw All-CI cases), we could not resolve within- and between-group differences in this sub-analysis. Similar to NASS-CDS, our sub-analysis that filtered for non-ejected occupants whose injuries likely occurred inside the rolling vehicle saw proportions (2.1%, 860/42,004 occupants) and relative risks (1.66, 0.55–4.99) diminish but had large confidence limits (Table S2 in the Supplemental Materials).

Discussion

The overall goal of this study was to examine how different types of cervical spine injuries vary with different occupant-related factors in rollover and, for comparison purposes, non-rollover crashes. To achieve this goal, we relied on weighted crashes from the NASS-CDS database for the years 2005–2015 and the CISS database for the years 2017–2022, and we focused our attention on occupants with vertebral or spinal cord injuries in the cervical spine. Across both databases, we found that most occupants with cervical spine injuries in rollover

Table 6 CISS (2017–2022) weighted counts and proportions (%) for (a) all exposed occupants (injured and uninjured) and (b) all injured occupants (occupants with cervical spine injuries) separated by their exposure to a rollover or non-rollover crash. Separate analyses are tabulated for cases where sex, seatbelt use, ejection status and fatality information was known. Abbreviations: R = rollover, NR = non-rollover, N = weighted counts, Nall = total weighted counts for each condition. The percentages for the rollover (R/N) and non-rollover (NR/N) conditions for each row sum to 100%, whereas the total column percentages (N/Nall) for each group sum to 100%

a) All Exposed Occupants

Group	Rollover		Non-Rollover		Total	
	R	R/N	NR	NR/N	N	N/Nall
Sex						
Female	178,674	4.7%	3,613,069	95.3%	3,791,743	54.2%
Male	203,241	6.3%	2,998,352	93.7%	3,201,593	45.8%
Total	381,915	5.5%	6,611,421	94.5%	6,993,336	100.0%
Seat belt use						
Belted	300,689	5.0%	5,687,375	95.0%	5,988,064	90.4%
Unbelted	56,343	8.9%	577,188	91.1%	633,531	9.6%
Total	357,032	5.4%	6,264,563	94.6%	6,621,595	100.0%
Ejection						
Ejected	4,727	66.7%	2,361	33.3%	7,088	0.1%
Not Ejected	366,229	5.2%	6,667,833	94.8%	7,034,062	99.9%
Total	370,956	5.3%	6,670,194	94.7%	7,041,150	100.0%
Fatality						
Fatal	4,868	17.7%	22,666	82.3%	27,534	0.4%
Not Fatal	381,048	5.4%	6,659,505	94.6%	7,040,553	99.6%
Total	385,916	5.5%	6,682,171	94.5%	7,068,087	100.0%

b) Injured Occupants Only

Group	Rollover		Non-Rollover		Total	
	R	R/N	NR	NR/N	N	N/Nall
Sex						
Female	8,022*	34.4%	15,280	65.6%	23,302	55.5%
Male	3,265	17.5%	15,437	82.5%	18,702	44.5%
Total	11,287	26.9%	30,717	73.1%	42,004	100.0%
Seat belt use						
Belted	8,049	31.2%	17,746	68.8%	25,795	66.2%
Unbelted	2,533	19.2%	10,663	80.8%	13,196	33.8%
Total	10,582	27.1%	28,409	72.9%	38,991	100.0%
Ejection						
Ejected	650	68.3%	301	31.7%	951	2.3%
Not Ejected	10,494	25.7%	30,374	74.3%	40,868	97.7%
Total	11,144	26.6%	30,675	73.4%	41,819	100.0%
Fatality						
Fatal	660	10.9%	5,398	89.1%	6,058	14.4%
Not Fatal	10,627	29.6%	25,319	70.4%	35,946	85.6%
Total	11,287	26.9%	30,717	73.1%	42,004	100.0%

* One of the 22 raw female cases had a weight of 3270

crashes involved only vertebral injuries (91 to 94%), and that spinal cord injuries occurred in only 6.0 to 9.1% of all occupants with cervical vertebral column injuries associated with rollover crashes. We also found that cervical spine injuries involving vertebral fractures were 5.2 times (NASS-CDS) to 6.4 times (CISS) more likely to occur in rollover crashes than in non-rollover crashes. Even for the subpopulations related to sex, seatbelt use, ejection and fatality, the relative risks in our CISS analysis remained similar to or greater than the relative risks in

our NASS-CDS analysis despite a presumably safer fleet of vehicles in the CISS database. Given the high societal costs associated with cervical spine injuries—especially spinal cord injuries—these findings highlight the importance of developing countermeasures aimed at either preventing rollover crashes from happening or preventing cervical spine injuries in rollover crashes that do happen.

Our CISS sample was smaller than our NASS-CDS sample and thus yielded wider confidence intervals, especially for the spinal cord injury group. Interestingly, while

Table 7 CISS (2017–2022) proportions and relative risks for all exposed occupants. Table summarizes the proportion (95th percentile confidence interval) of each injury type experienced in rollover crashes (top row) and the relative risk (95th percentile confidence interval) of experiencing each injury type in a rollover crash compared to a non-rollover crash for all occupants (first row of relative risks) and for subgroups of female/male, belted/unbelted, and ejected/not ejected occupants (bottom pairs of rows of relative risks)

All Exposed Occupants

Injury Group	All-VI		All-CI		All-Injuries	
	(VI + VCI)		(CI + VCI)		(VI + CI + VCI)	
Proportion in rollover (%)	27.45%	(7.07–47.84)	14.94%	(0.00–31.71)	26.87%	(7.48–46.26)
Relative Risks						
All Occupants	6.55	(2.18–19.71)	3.04	(0.64–14.41)	6.36	(2.21–18.33)
Females	11.52	(2.64–50.31)	-	-	10.62	(2.49–45.27)
Males	2.75	(1.38–5.48)	4.56	(0.92–22.63)	3.12	(1.68–5.80)
Belted	9.12	(2.32–35.82)	2.40	(0.44–13.12)	8.58	(2.22–33.13)
Unbelted	2.23	(1.13–4.41)	2.94	(0.43–20.06)	2.43	(1.25–4.74)
Ejected	1.17	(0.29–4.73)*	0.71	(0.03–15.22)	1.08	(0.26–4.40)*
Not Ejected	6.45	(2.05–20.26)	3.06	(0.63–14.83)	6.29	(2.11–18.79)
Fatal	0.59	(0.17–2.01)*	0.27	(0.01–4.86)	0.57	(0.16–1.99)*
Not Fatal	7.49	(2.41–23.23)	4.01	(0.82–19.59)	7.34	(2.47–21.81)

* Significant difference (*p* < 0.05) between the relative risks of the two subgroups (e.g., fatal vs. not fatal)

- There were no instances of females in rollovers with spinal cord injury
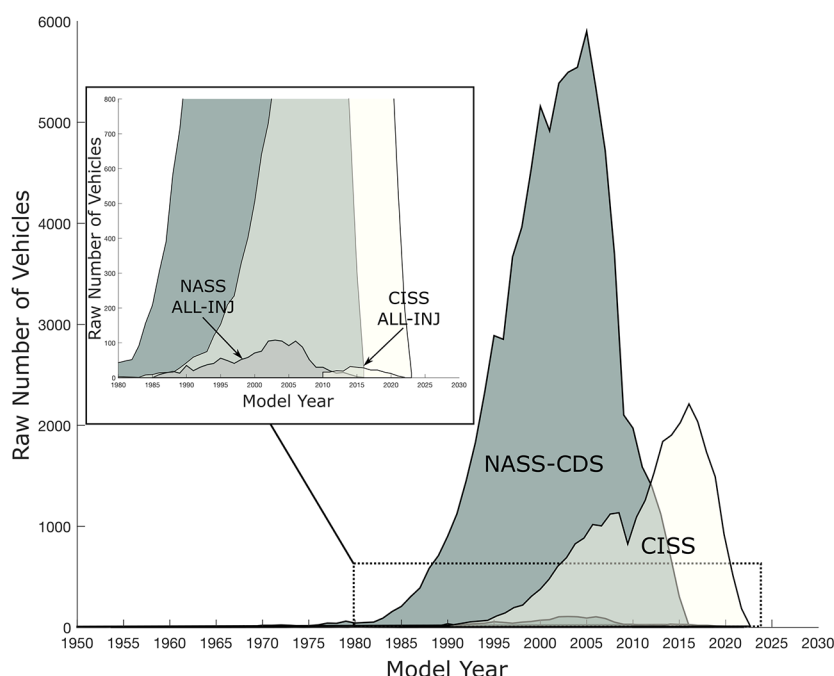
Fig. 2 Model years of crash-involved vehicles for NASS-CDS and CISS. The raw numbers of vehicles per model year are shown for NASS-CDS (2005–2015) and CISS (2017–2022) data. The inset graph shows a zoomed in view of the All-Injuries groups in both analyses

relative risks in the CISS and NASS-CDS analyses were similar, annual injury rates dropped disproportionally in our CISS data (from 10,095 cervical spine injuries per year in NASS-CDS to 7,001 cervical spine injuries per year in CISS). To determine if this drop was due to vehicle improvements or solely due to the narrower model and crash year filter in the CISS analysis, we reran the NASS-CDS analyses using 2010–2015 data and MODE-LYR ≥ 2002 to match the ranges used in the CISS analysis.

Annual NASS-CDS case numbers decreased to 6,229 injuries per year, and relative risks were lower than in the original NASS-CDS analysis (Table S3 in the Supplemental Materials). One possible explanation for these findings is that safety improvements in the newer fleet may be offset by an increase in the number of vehicles more prone to rollovers (e.g., SUVs and trucks) (Statista Market and Insights 2023). In partial support of this explanation, a post hoc analysis revealed that 21.7% of occupants with

cervical spine injury in the NASS-CDS dataset were in utility vehicles, whereas 50.6% of occupants with cervical spine injuries in the CISS dataset were in utility vehicles. Further work exploring the interaction of safety improvements and fleet composition is warranted.

Although rollovers have a higher risk than non-rollovers of causing cervical vertebral injuries (NASS-CDS and CISS data) and spinal cord injuries (NASS-CDS data only), these increased risks were not significantly different between females and males ($p > 0.60$ in both NASS-CDS and CISS). This finding is consistent with previous rollover-specific research (Funk et al. 2012; Ivarsson et al. 2015). Sex, however, is a complex variable that combines many intrinsic factors (e.g., height, weight, vertebral size, vertebral tolerance to load, neck length, neck strength, etc.) (Ezra et al. 2017; Pan et al. 2018; Vasavada et al. 2008) that could interact with various extrinsic factors (e.g., seat geometry, seat belt fit, occupant compartment geometry, etc.) to wash out specific sex differences that potentially could be leveraged to improve occupant protection. Further work is needed to explore the potential interaction of these factors and whether they influence cervical injury outcomes differently for females and males.

Similar findings were observed in relation to seatbelts, where the relative risks of sustaining different cervical spine injuries in rollover and non-rollover crashes were not significantly different for belted and unbelted occupants (NASS-CDS: $p > 0.64$, CISS: $p > 0.44$). Many prior studies have shown that unbelted occupants are at higher risk for injury than belted occupants (Bedewi et al. 2004; Funk et al. 2012; Moore, 2005; Parenteau and Viano 2014), and our data aligns with prior findings that proportionally more cervical spine injuries occur in rollovers than in non-rollovers (Parenteau and Viano 2014; Yadollahi et al. 2016; Yoganandan et al. 1989a); however, our data also shows that there is no specific category of cervical spine injury that is disproportionately more or less likely in rollovers than in non-rollovers between belted and unbelted occupants. This finding is perhaps surprising given that unbelted occupants include virtually all ejected occupants, who have much higher risks of sustaining a cervical spine injury than those who are not ejected. For instance, in a post hoc analysis of rollovers in the NASS-CDS data, ejected occupants were 8.8 (6.2–12.3) times more likely to have a vertebral injury (All-VI group) than non-ejected occupants, and in non-rollovers, ejected occupants were 50 (23–110) times more likely to have a vertebral injury (All-VI group) than non-ejected occupants. In absolute terms, however, the number of ejected occupants is small (<1% of all exposed occupants, with about two-thirds occurring in rollover crashes; Tables 3 and 7), and therefore their influence

on the relative risk values may be too small to affect the overall relative risks.

Within ejected occupants in our NASS-CDS analysis, the relative risks for cord-related injuries were significantly less than one (RR = 0.14, Table 4), indicating that ejected occupants in rollovers were less likely to have a spinal cord injury than ejected occupants in non-rollover crashes. The corresponding relative risk for the CISS analysis was also less than one, but the low sample size rendered it not significant. A post hoc analysis of the NASS-CDS data revealed that in rollover crashes, ejected occupants were 5.4 (1.7–17.1) times more likely to have a spinal cord injury (All-CI group) than non-ejected occupants, and in non-rollover crashes, ejected occupants were 157 (41–604) times more likely to have a spinal cord injury than non-ejected occupants. From a spinal cord injury perspective, this finding may imply that it is much worse to be ejected from a non-rollover crash than a rollover crash. One possible explanation for this phenomenon is that ejected occupants in non-rollover crashes experience more severe collisions than non-ejected occupants. Indeed, a follow-up calculation showed that the speed change (DVTOTAL) in non-rollover crashes was 36.6 ± 2.5 km/h (mean $\pm$ SE) for ejected occupants compared to 19.8 ± 0.1 km/h for non-ejected occupants. A similar comparison for rollover crashes is less meaningful because ejection is likely related more to angular roll speed and vehicle configuration, window damage and deformation that allows for ejection than to the linear speed change of any single impact during a rollover event, and roll speed is not recorded in the NASS-CDS database. Nevertheless, these findings highlight that ejection is a serious risk for cervical spinal cord injury in both rollover and non-rollover crashes.

We found that 18% (5,724/31,236 in Table 3b) of NASS-CDS rollover occupants with cervical spine injuries were fatally injured, a rate that is almost 10 times higher than the general fatality rate in rollovers (1.9%, 31,687/1,684,859 in Table 3a). In non-rollovers, however, 24% (19,597/79,804 in Table 3b) of occupants with cervical spine injuries were fatally injured, a rate that is 70 times higher than the general fatality rate in non-rollovers (0.35%, 75,258/21,519,969 in Table 3a). CISS data followed a similar trend but with lower overall fatality rates. In rollovers, 5.9% (31,687/1,684,859 in Table 6b) of occupants with cervical spine injuries were killed, about 5 times the general fatality rate of 1.3% (4,868/385,916 in Table 6a), whereas in non-rollovers, 17.6% (5,398 /30,717 in Table 6b) of occupants with cervical spine injuries were killed, about 53 times the general fatality rate of 0.3% (22,666 /6,682,171 in Table 6a). An explanation for why the fatality rate of cervical-spine-injured occupants is higher in non-rollovers than rollovers cannot be

reached here due to missing injury information for many fatal cases in both NASS-CDS and CISS.

Even though we restricted our CISS database analyses to vehicles manufactured in and after 2010, the relative risks and rollover proportions in the CISS analysis were similar or greater than those in the NASS-CDS analysis (compare Table 4a and Table 7). Since 2010, the vehicle fleet underwent major advances in safety systems, e.g., the introduction of roof strength (FMVSS No. 216a, 2009) and ejection mitigation (FMVSS No. 226, 2011) legislation. As might be expected, there was a 5.6- to 6.9-fold reduction in ejections for both the exposed and injured populations (Tables 3 and 6) in rollovers and non-rollovers. However, the relative risks for vertebral injuries remained high in the later model vehicles included in our CISS analysis. Advances in passive safety may have been successful in reducing the number of injured occupants per year, however, rollover-specific technology, like roof airbag systems and roof designs (Halldin et al. 2000; Heudorfer et al. 2005; Lee 2021) may be needed to target rollover-specific occupant impact mechanisms that have not been addressed by existing technology.

Many cadaveric experiments (Alem et al. 1984; McElhaney et al. 1983; Nightingale et al. 1991; Pintar et al. 1989; Yoganandan et al. 1989b) have sought to quantify injury thresholds and responses of the cervical spine to axial compression but have failed to consistently reproduce real-world injury patterns that occur in automotive rollovers (Foster et al. 2012). Nevertheless, clinically relevant cervical spine fractures are consistently caused by headfirst impacts that compress the cervical spine in cadaver experiments (Nightingale et al. 1996a, b, 1997; Saari et al. 2011). Moreover, these fractures occur early (2 to 19 ms after head contact), well before any significant head motion develops and well before reflex muscle activation could develop in living humans. The early occurrence of these fractures indicates that they are likely caused by local flexion and extension buckling of the cervical spine due to compression rather than excessive flexion, rotation or extension of the head and neck (Nightingale et al. 2019). Posterior injuries and other injuries associated with spinal loads absent axial compression like the "Clay-shoveler's" fracture were found to be rare in our dataset (~ 8% of injuries in CISS) and in previous studies examining both rollovers and non-rollovers (Foster et al. 2012).

Here, we sought to find injury patterns unique to rollovers, as the kind of cervical spine injury an occupant sustains may reveal the underlying initial conditions of the headfirst impact leading to axial loading of the neck (Winkelstein and Myers 1997). Despite the rare occurrence of cervical spinal cord injuries, we found that 73 and 77% of cervical spinal cord injuries in the NASS-CDS dataset (50 and 90% in CISS) had associated fractures or fracture-dislocations in non-rollover and rollover occupants, respectively. These results suggest that there is a strong relationship between spinal cord injuries and the presence of fractures and/or fracture-dislocations, a finding that is consistent with clinical evidence of the prevalence of these injuries in both motor-vehicle collisions and other contexts (Sekhon and Fehlings 2001). Future efforts aimed at preventing vertebral and spinal cord injuries that prioritize reducing cervical spine fractures will simultaneously reduce cervical spinal cord injuries as well.

The generalizability of our analysis is limited by some of our methods. Our analysis included injuries that may have occurred before or after the rollover itself. Previous researchers (Bose et al. 2011; Funk et al. 2012; McMurry et al. 2016) saw a large decrease in cases when they tried to restrict their data to pure rollovers without planar impacts. Bose et al. (2011) proposed that ignoring the contribution of associated planar impacts might alter vehicle intrusion and the occupant's initial position, two factors that could affect injury risk. When we attempted to isolate only those injuries that occurred during the rollover and also excluded planar impacts (Table 4b), we found similar ($p > 0.36$), albeit reduced, relative risks. One limitation of using the NASS-CDS and CISS databases is a lack of in-depth injury documentation that could help further ascertain injury patterns unique to rollovers. While data from the CIREN includes imaging and autopsy data, its small sample size is insufficient to perform the analyses described in this study. Also, we chose to differentiate cervical spine injuries based on whether the cord was involved or not. An alternative differentiation could be based on benign and clinically relevant injuries, however both NASS-CDS and CISS rely on AIS codes that are not well suited for such differentiation.

Our study was aimed at describing the occupant cohort who sustained cervical spine injuries and to contrast them between rollovers and non-rollovers. We used occupant variables, like sex, belt status, ejection, and fatality to describe how these sub-groups were correlated with injury outcome. We did not repeat prior analyses on crash-related factors known to influence rollover injury severity, like the number of rolls, the extent of roof crush, roll direction, and the occupant's seat position (Hu 2007; Hu et al. 2007; McMurry et al. 2016; Padmanaban 2005; Parenteau 2001; Viano and Parenteau 2018). While we acknowledge the importance of these other crash-related factors, combining these other factors with our variables of interest led to sample sizes that were too small to yield meaningful insights.

Our NASS-CDS analysis relied on data from the last 11 years of this database and included vehicle model years 1985 to 2016. Safety improvements to vehicles since 2015 were not captured in our NASS-CDS analyses. In

particular, the increased use of side curtain airbags in the vehicle fleet (which is not recorded in NASS) could affect the relative risks we report here (Li et al. 2018). Despite a recent trend of using combined CISS and NASS-CDS data to gain statistical power (Craig et al. 2024; Viano and Parenteau 2023), our approach enabled us to see the persistent high rates of cervical spine injuries in rollovers. Moreover, a comparison of vehicle model years between the NASS-CDS and CISS datasets (Fig. 2) revealed substantial overlap between the entire fleets in the two databases, but relatively little overlap in our injured population due to our model-year filters.

Conclusions

In summary, we sought to characterize the relative frequencies and relative risks of different types of cervical spine injuries in rollover and non-rollover crashes. Despite accounting for only 7.3% of collisions in NASS-CDS (5.5% of collisions in CISS), rollovers generated 23% (15%) of cervical spinal cord injuries and 28% (28%) of cervical vertebral injuries. The relative risks for cervical vertebral and spinal cord injuries were 3.4 to 5.2 times (CISS: 3.0 to 6.6 times) higher in rollover than in non-rollover crashes. These relative risks were similar for male and female occupants, belted and unbelted occupants, non-ejected occupants, and non-fatal occupants. Despite advancements in vehicle safety technology in the CISS crashes, these proportions and risks remained disproportionally high for rollover occupants across both databases. There was no specific category of cervical spine injury that was more or less likely in rollovers, although vertebral injuries were more common (NASS-CDS: 91.5%, CISS: 94.3%) than spinal cord injuries (11.5%, 6.0%). Lastly, these findings suggest that research focused on preventing cervical vertebral fractures will prevent serious and debilitating injuries to the spinal column while also effectively preventing most cervical spinal cord injuries.

Abbreviations

AIS	Abbreviated injury scale
ATD	Anthropometric test device
CIREN	Crash injury research engineering network
CISS	Crash investigation sampling system
FMVSS	Federal motor vehicle safety standard
NASS-CDS	National automotive sampling system – crashworthiness data system
NHTSA	National highway traffic safety administration
PSU	Primary sampling unit
RR	Relative risk
SCI	Spinal cord injury

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40621-024-00506-4.

> Supplementary Material 1

Declarations

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