Occupant Injuries Related to Rollover Crashes and Ejections from Recent Crash Data

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ABSTRACT

The goal of this paper is to determine the recent annual occupant populations and trends related to rollover injuries and fatalities, and to assess the risk factors that may have significantly contributed to occupant injuries and fatalities when rollovers and ejections occur. Fatality Analysis Reporting System (FARS) 2004-2017 data were used to obtain the recent occupant fatalities related to rollovers and ejections. National Automotive Sampling System (NASS) – Crashworthiness Data System (CDS) 2013-2015 weighted survey data were used extensively to estimate the occupant injury severities and occupant ejection details associated with rollovers. For rollover cases, the injured body regions (e.g., head, neck, shoulder and back, and chest) and injury contact sources (e.g., vehicle roof, side door, or seat back) were investigated in detail. This study paid close attention to the interaction between the vehicle roof and occupant injuries for the consideration of the requirements from Federal Motor Vehicle Safety Standards (FMVSS) 216a and 226. Finally, occupant injury risk and key risk factors were evaluated using methods of relative risk, including multiple logit model and case-control study. The data analysis using FARS showed a decrease in annual fatalities from approximately 10,500 during 2004-2006 to approximately 7,000 during 2014-2017. Approximately one thirds of all occupant fatalities of light passenger vehicles (Gross Vehicle Weight Rating, GVWR <=10,000 lbs.) are related to rollovers. FARS data also provided the occupant ejection status (complete or partial ejection) and ejection path associated with rollovers. The CDS data indicated that rollovers are strongly associated with the injury sources of vehicle roof, side doors, and seat back/support; rollover crashes also resulted in primarily the injured body regions of head, neck, shoulder/back, and chest. The occupant ejection paths are usually side windows and roof opening. The analytical results also revealed that light trucks /vans, with relatively higher centers of gravity, tend to have relatively higher likelihood of rollover crashes than passenger cars, but passenger cars tend to result in a higher rate of occupant serious injuries (Maximum Abbreviated Injury Scale 3+, or MAIS 3+) than light trucks/vans, if rollovers did occur. Overall this study explored the trends and annual occupant populations related to rollovers and ejections using recent traffic data. Logistic regression model was used, with considerations of multiple risks and confounding factors, to predict the occupant injury relative risks of several key risk factors simultaneously. The analytical results using both FARS and CDS indicated that higher occupant injury risks were especially associated with higher delta-V, unbelted occupant, rollover, ejection, side impact, and older occupant age. This study, utilizing the recent crashes from three main databases of FARS, NASS CDS and NASS General Estimates System (GES), may enrich the understanding of rollover and ejection related occupant injuries.

1. INTRODUCTION AND DATA

National Highway Traffic Safety Administration (NHTSA) has been working constantly to improve vehicle safety and reduce traffic injuries. The total traffic fatalities (including occupants, pedestrians and cyclists) for the past few years are 32,744 in 2014, 35,806 in 2015, and 37,461 in 2016 (approximately 37,133 in 2017 from the recent release). Approximately two-thirds of all traffic fatalities are from the occupants killed of light passenger vehicles (cars and light trucks /vans with GVWR less than 10,000 lbs.), furthermore, approximately one-thirds of those occupant fatalities of light passenger vehicles come from rollover crashes. Vehicle rollover is a very risky crash mode that causes severe injuries to occupants, especially to the head, shoulder & back, face, neck and chest from contacts between occupants and vehicle roofs and side doors, or from ejection out of vehicles.

Rollover crashes have previously been identified by NHTSA as a high safety priority, and work has been done investigating potential countermeasures [1, 2, 3, 4, 5]. Recently enacted FMVSS (and now fully implemented), such as FMVSS 126 (Electronic stability control systems for light vehicles), FMVSS 216a (Roof crush resistance) and FMVSS 226 (Ejection Mitigation), have sought to reduce the incidence of rollovers, improve vehicle crashworthiness during rollovers and reduce the likelihood of ejections during rollovers. Thus, it is of interest to update the previous understanding on rollovers and injury risk, with different vehicles ages and newer data.

Data sources for this study include FARS (which contains a census of all vehicle fatalities), and the two data systems of NASS, e.g., CDS and GES. The general trends of crashes of all vehicle types and injuries of all person types can be obtained from GES, on the other hand, CDS will be most extensively used throughout this study for occupant injury details associated with light passenger vehicles. CDS data have previously been used by many NHTSA researchers to investigate crash injury details and risk factors, such as weighting factor designs of survey data, vehicle damage areas (frontal crash or side impact), occupant seating position and belt use, delta-V, occupant injured body regions, the vehicle components that contacted the occupants within a crashed vehicle, and occupant injuries and time to medical treatments [6, 8, 9, 10, 11, 12, 19]. A similar approach is used for the current research.

CDS contains several independent data files that describe vehicle crashes and occupant injury details. The data file of 'General Vehicle' (GV) provides the crash details related to the towed crashed vehicles (i.e., vehicle type, model year, vehicle weights, delta-V, crash type and rollover status). The data file of 'Occupant Assessment' (OA) provides the occupant information (e.g., occupant age, gender, belt use, drinking status, seating position, ejection and ejection area, injury scales, or MAIS). Similarly, the 'Occupant Injury' (OI) data file provides detailed injured body regions (e.g., head, face, AIS scale, and others) and injury sources of vehicle components (roof, door, B-pillar, seat back, or others). The 'Vehicle External' (VE) file provides the principal crash damage areas (e.g., frontal damage, or side damage, useful for identifying the crash directions and crash modes), and 'Accident' (ACC) data file has information about crash location, road, weather, and case number. Starting in 2009, the CDS system collected crash data only from newer vehicles of age <=10 years old only. Therefore, for this research, the vehicle age was limited to within ten years for most analysis (crash year – model year <= 10). The primary CDS data files related to vehicle crash types and occupant injuries, e.g., 'GV', 'OA', 'VE', 'ACC', or 'OI', can all be sorted and merged together by using 'crash year, PSU, case number, vehicle number, and occupant number'. Statistical Analytical System (SAS) procedures of '*sort*' and '*merge*' are used to sort and link the data files of research interest together for this data flow-chart design. SAS version 9.3 was used for this study. [16, 17]

A detailed flowchart of using CDS data, described in Figure 1, provides the overall approach to examine the research questions. For example, merged "GV+OA" data by using 'crash year, PSU, case number, and vehicle number', with auxiliary information of vehicle external (VE) damages, can answer the questions related to overall occupant fatality and injury, vehicle damage areas, rollover, and occupant seating and maximum occupant injuries (MAIS). In the final step, the correlations, between the occupant injuries and several main independent risk factors, are examined using multiple regression model.

The objectives of this study are to continue the earlier injury research efforts and better understand the injury causes related to rollovers and ejections. Some questions of special interest, step-by-step, are summarized as follows:

- How many occupants (drivers and passengers) of light vehicles died from rollover crashes? FARS data provide complete descriptions of fatalities related to rollovers and ejections.
- How many vehicles (passenger cars and light trucks/vans not more than 10,000 lbs.) are involved in rollover crashes annually? Both GES and CDS data can provide estimates of rollover incidence.
- How many occupants are injured from rollovers annually? CDS data will be used to look at detailed injury severities associated with various vehicle types and crash modes.
- What body regions are commonly injured in rollovers (e.g., an occupant may suffer injuries in several body regions)? What are the most prevalent injury sources (e.g., vehicle roof, side door, B-pillar) that contact occupants in rollovers?
- If rollover and ejection occur, what are the common ejection paths (e.g., roof opening or side windows)?
- If there is an interaction between the vehicle roof and occupant, what are the common injured occupant body regions (e.g., head, neck, spine)?
- More generally, if rollovers, either lateral or longitudinal crashes, and other risk factors are considered simultaneously, what are the relative risks from each factor (e.g., comparing the injury odds of rollover versus non-rollovers, belted vs. not-belted occupants)? This study explores this question using a multiple regression model.
- Finally, FMVSS 216a and 226 have certain impacts on vehicle rollovers /ejections, especially for vehicle models after 2011. This study explores the effect of vehicle age (<=2, <=4, and <=10 years old, respectively), and uses recent CDS data from the past ten years.

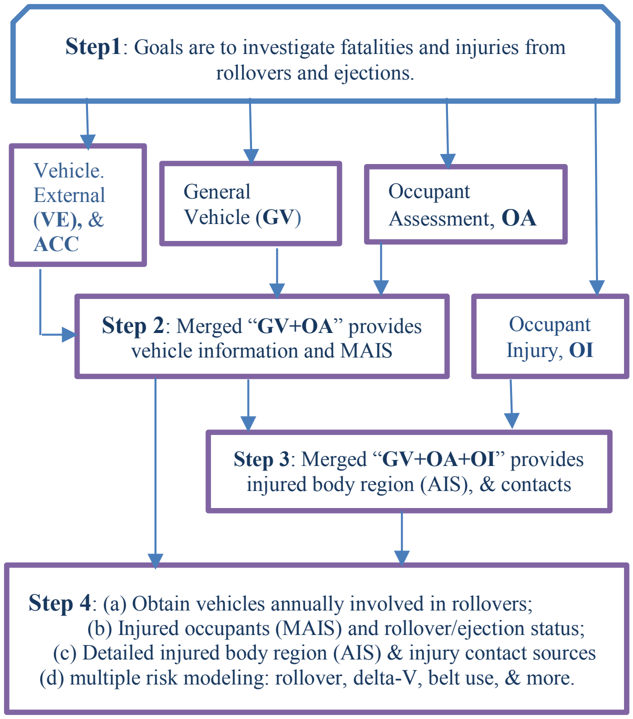

Figure 1: *Data Flow-Chart for obtaining Occupant Injuries related to Rollover and ejection using CDS Data*

A similar but much simpler flow-charts, using FARS or GES data files of 'Accident', 'Vehicle', and 'Person', can be done as Figure 1.

2. OCCUPANT FATALITIES RELATED TO ROLLOVERS AND EJECTIONS

FARS is a census of fatalities resulting from all types of crash modes. Three main data files, 'Accident', 'Vehicle', and 'Person', from the FARS database are used in this analysis. Several variables in FARS are of special interest, such as 'rollover', 'ejection', 'ejection path', and 'injury severity', and these key variables are used to answer various research questions.

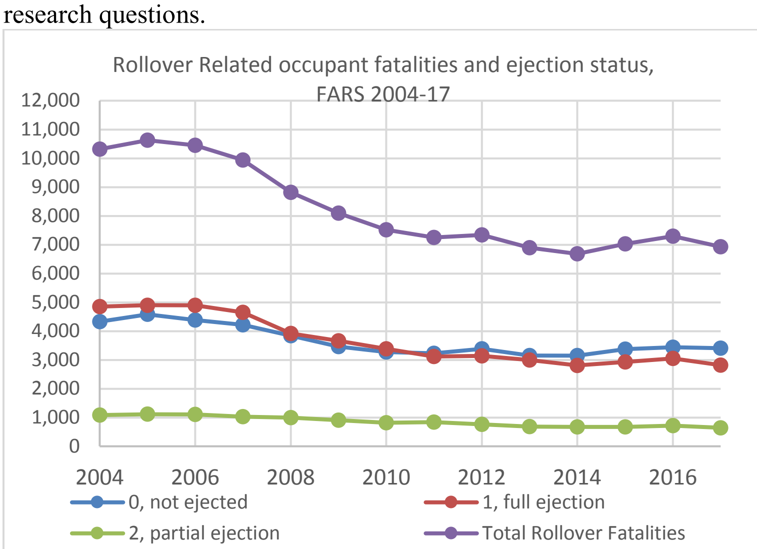

Figure 2: *Rollover-crash related occupant fatalities and ejection status (FARS 2004-2017, car or light truck/van GVWR <=10,000 lbs.)*

Figure 2 provides the rollover-related fatality 14-year trends using FARS 2004-2017 for occupants of light passenger vehicles (cars and light trucks/vans GVWR <= 10,000 lbs.). The total occupant fatalities due to rollover crashes decreased from 10,627 in 2005, to a lower 6,681 in 2014, and then slightly increased to approximately 6,933 in 2017. The annual average of rollover-related occupant fatalities was 8,227 during 2004-2017. Figure 2 shows the ejection status of either 'not ejected', 'partial ejection', or 'full ejection' out of all rollover-related occupant fatalities, and the occupant fatalities include the occupants (driver or passenger) in the motor vehicles-in-transport only (not including the vehicles-not-in-transport).

For passenger cars and light trucks /vans, the percentage (%) of rollover-related occupant fatalities among all occupant fatalities dropped from the high peak of approximately 35% during 2008-09 to the lower values of approximately 31% in 2016 and 30% in 2017, and this percentage decreasing trend was especially obvious during 2011-2017, as shown as Figure 3. The extensive efforts for higher fitment of vehicle stability control and stronger roof designs may have helped to reduce the rollover-related fatality percentage during recent years. [1, 3]

Vehicle rollovers often result in occupant ejections. Figure 4 shows ejection paths of light passenger vehicle occupants during rollovers. The average number of occupant fatalities during ejections out of the roof opening (sunroof, moonroof or others) is 87 during the 14 years of 2004-2017, but this number is higher, 97 and 109, in 2015 and 2016, respectively. Figure 4 also indicates that the 'side windows' are the most frequent ejection path, with an average of 773 fatalities during 14 years. The highest number of fatalities from side window ejection occurred in 2005 (1064), while the lowest occurred in 2016 (593) and in 2017 (576). The occupant fatalities associated with various known ejection paths (e.g., side windows, roof, etc.) are approximately 15% of rollover-related fatalities (unknown ejection paths are commonplace and FARS data contain complete fatalities but only partial injuries).

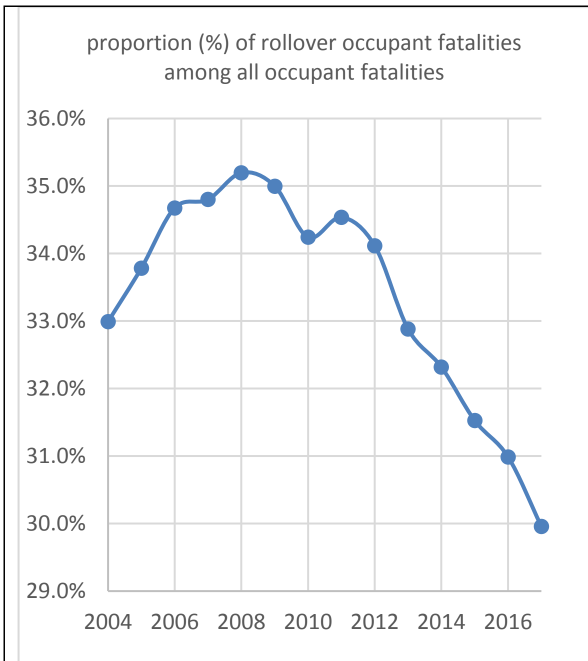

Figure 3: *Proportion (%) of occupant fatalities related to rollover crashes among all occupant fatalities (FARS 2004-17, passenger cars and light trucks/vans GVWR <=10,000 lbs.)*

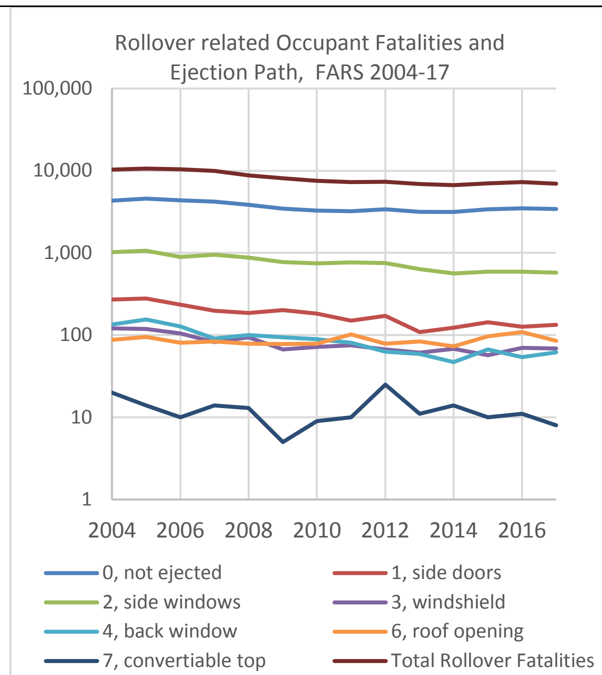

Figure 4: *Ejection paths of occupant rollover fatalities among occupant fatalities (from FARS 2004-2017, for light passenger vehicles <=10,000 lbs.)*

When rollovers occur, belt or restraint use is critically important to occupant safety. Although FARS does not contain details of specific injuries, the data clearly indicate the belt effect by relative comparison of injuries of 'unbelted' occupants versus the 'belted' (Table 1). In Table 1, the unbelted group has a fatal incidence of 70,796/105,521 = 67.1%. However, in the belted group, the fatal incidence is 33,423/84,441 = 39.6%.

Table 1: *Belt use status and occupant fatalities related to rollover crashes (light passenger vehicles GVWR <=10,000 lbs., FARS 2004-2017)*

Belt status	Fatal Injury	Not fatal	Total Occupants
Unbelted	70,796	34,725	105,521
Belted Occupants	33,423	51,018	84,441

Hence, the relative risk (RR) of fatal injury when unbelted versus belted is 0.671/0.396=1.7; and the fatality Odds Ratio (OR) of unbelted versus the belted is 3.1. The interpretation is that an unbelted occupant's odds of fatality are approximately 3 times compared with the belted occupant, if a rollover occurred. In this comparison, only one risk factor (belt use) is considered without considering other risk factors. Similar two-by-two table can be made for heavier vehicles with GVWR over 10,000 lbs. If multiple risk factors of belt use, occupant age, travel speed (crash severity, or delta-V), and rollover are considered simultaneously, a multiple regression approach is discussed in section 5.

3. ROLLOVER TREND FROM GES

To examine how many vehicles are involved in rollovers annually, GES 2006-15 weighted data from 36 Primary Sampling Units (PSU) can provide more general annual trends and populations of crashes of various vehicle types and injuries of all person types. The weighted annual averages of light vehicles and other vehicle types, if involved in rollover crashes during 2006-2015, are listed as Table 2.

Table 2*: Weighted Annual Vehicle Types Involved in Rollover Crashes (GES 2006-15, including all model years)*

Year	combination truck	Single unit truck	bus	car & light truck /van
	GVWR >10,000 lbs.			<=10,000 lbs
2006	9,769	5,645	55	251,543
2007	9,461	5,385	111	263,058
2008	7,303	4,307	67	248,543
2009	6,333	3,117	0	213,675
2010	6,344	2,916	17	189,445
2011	6,343	2,722	233	184,867
2012	8,124	4,442	229	196,236
2013	7,046	3,809	139	184,082
2014	9,047	4,030	20	199,734
2015	6,909	4,698	0	193,349
Total	76,678	41,070	871	2,124,530

The weighted averages of light passenger vehicles (GVWR <=10,000 lbs.) involved in rollovers from GES data may be used as a reference to the similar rollover results from CDS data. [6, 7]

4. ROLLOVER AND INJURED OCCUPANTS FROM CDS

CDS data, that are survey data from 24 PSU and focused on the crashes of light passenger vehicles (GVWR not more than 10,000 lbs.), include details of occupant injuries and vehicle crash conditions. Recent CDS data (from 2013-2015 mainly) are used in this study to explore occupant injuries from rollover crashes. In CDS, occupant injuries are coded using AIS, a numerical scale system by Association for the Advancement of Automotive Medicine (AAAM) to rate the injury severity (e.g., AIS 0=not injured, 1=minor injury, 2=moderate injury, 3=serious injury, 4=severe injury, 5=critical injury, 6=maximum injury or fatal, 7=injured but severity unknown), although a high percentage of AIS codes are missing or unknown. In CDS data, each occupant injury is assigned an AIS severity level and each injured body region has a maximum severity AIS injury level within that body region. Also, one value of overall Maximum AIS (e.g., MAIS, the maximum AIS severity from all body regions) for each occupant, hence, each occupant has one count of MAIS and may have several regional AIS results. The data flow-chart of Figure 1 is used extensively for CDS data analysis, this flow-chart analyzed the 'top-down' data structure in CDS and searched the vehicle crashes and occupant injury details from 'Accident' to 'Vehicle', then to 'Occupant', and finally 'Injured Body Region' or 'Contact Source' were searched. All listed results are from weighted data calculations (Tables 3-7 and Figures 5-15).

CDS survey data are associated with weighting factor for each crash, the general 'weighted population mean', $\bar{y}$, is defined by following formula: [6, 8, 13]

$$\bar{y} = \frac{\sum_{i=1}^{n} \omega_i \, y_i}{\sum_{i=1}^{n} \omega_i} \qquad \text{Eq. (1)}$$

where 'y_i' is the value of 'i-th' unit or crash, and 'ω_i' is the weighting factor associated with 'i-th' unit or crash. The weighting factors in CDS came from the three-stage sampling designs, in which the selection of each PSU among 24 PSUs, the probability of crashes selected by police in each PSU, and the selections of various crash severities /types were considered statistically, stage-by-stage. [6, 8]

4.1 Cars and Light Trucks Involved in Rollovers and Occupant Injury Comparison

First, overall numbers of vehicles (passenger cars and light trucks) involved in 'rollover' crashes or 'non-rollover' crashes were obtained. 'Rollovers' were further categorized as "side rollovers 1-3 quarter", "side rollover >=4 quarters" (quarter refers to number of quarter turns during the rollover, each quarter is 90 degrees of revolution), and "end to end rollover /tilt"; non-rollover crashes were categorized as single vehicle plane damaged (front damage, side damage, rear damages or top/under damage), or multiple vehicle planes damaged, as described in Figure 5 and Table 3. Secondly, the number of occupants injured from passenger cars and light trucks was determined, from both rollover and non-rollover crashes (Table 4).

During the years of 2013-2015, approximately 161,000 (annual weighted average including all model years) passenger cars and light trucks were involved in rollover crashes, and rollover crashes comprised approximately 6% of all crashed vehicles of approximately 2.7 million annually, shown in Table 3. Furthermore, Table 3 shows that passenger cars experienced a smaller percentage of rollover crashes (3.7%) among all car crashes than the light trucks (10.3%).

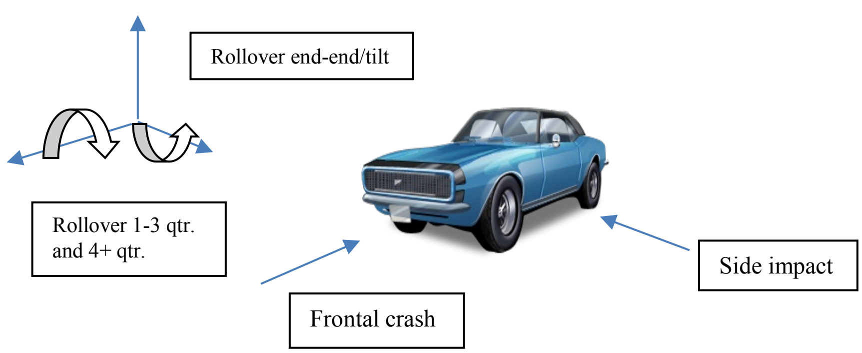

Figure 5: *The rollover types of light passenger vehicles (car or light truck/van in CDS, GVWR <=10,000 lbs.)*

Table 3: *Annual weighted averages of passenger car and light truck/van crash types ('Rolled' and 'non-Rolled', CDS 2013-2015, GVWR <=10, 000 lbs.*)

Crash Types of Passenger Cars	**Crash Modes of Light Trucks/Vans**
Rollovers 1-3 Quarter: 48,063 Rollovers 4+ Quarter: 19,050 Rollovers end-end: 815 **Total Rolled Cars: 67,928**	Rollovers 1-3 Quarter: 53,225 Rollovers 4+ Quarter: 39,188 Rollovers end-end: 641 **Total Rolled Trucks: 93,054**
single front damage: 229,309 single side damage: 76,927 single rear-damage: 4,796 single top/under damages: 9,904 multiple front damage: 807,459 multiple side damage: 407,182 multiple rear-damage: 194,483 multiple top/under damages: 1,948 **Total non-Rolled Cars: 1,732,008**	single front damage: 103,484 single side damage: 25,215 single rear damage: 529 single top/under damage: 1,636 multiple front damage: 416,958 multiple front damage: 190,947 multiple front damage: 69,461 multiple front damage: 527 **Total non-rolled Trucks: 808,757**

It is known that light trucks or vans, in general, have higher centers of gravity than passenger cars, and Table 3 using CDS 2013-2015 indicated that light trucks or vans tend to rollover more frequently than passenger cars.

The occupant injury rates from passenger cars and light trucks/vans were different, too, which shared the similar trends as vehicle crash data of Table 3. From a perspective of injured occupants within light passenger vehicles, Table 4 indicates that passenger car occupants (injured or not) involved in rollovers count approximately 3.4%, or 83,917 divided by (83,917+2,359,792) of all car crash occupants; while the light truck/van occupants involved in rollover crashes count approximately 10.3%, or 134,146 divided by (134,146+1,170,789). All model years of light vehicles were included in Tables 3, 4.

Table 4: *Annual weighted Averages of Occupant Injuries (MAIS) of Light Passenger Vehicles (CDS 2013-15, Rollover, 'R', vs. Non-Rollover, 'N'*)

Car Occupant Injuries (by MAIS)							
	unknown	MAIS=0	1	2	3 -6	7	Total
R	39,137	16,295	19,557	4,438	2,813	1,676	83,917
N	1,059,612	834,998	347,400	65,381	19,987	32,414	2,359,792
Light Truck/Van Occupant Injuries (by MAIS)							
	unknown	MAIS=0	1	2	3 -6	7	Total
R	90,526	11,923	24,608	3,460	3,037	591	134,146
N	564,165	440,081	128,403	22,698	6,178	9,263	1,170,789

Passenger car occupants are more likely to be seriously injured when in a rollover crash, compared with a non-rollover. Table 4 indicates that approximately 2,813 car occupants are seriously injured (MAIS =3,4,5,6) in rollover crashes annually (weighted data of MAIS 3=1948, MAIS 4=479, MAIS 5=212, MAIS 6=174), which is 4.2% of the total number of injured car occupants in rollovers (MAIS not 0, or 67,622 annually). For non-rollover crashes, approximately 19,987 car occupants are seriously injured (MAIS = 3,4,5,6) (14,532 + 3737 + 1169 + 549), or only 2.7% of all injured car occupants (MAIS not 0, or 730,708 annually) of non-rollover cars. Hence, rollover crashes usually result in more serious injuries than other crash types for car occupants.

For light trucks/vans, seriously injured occupants (MAIS =3,4,5,6) make up of 2.5% of all injured occupants in rollovers (MAIS not 0). For non-rollovers, seriously injured occupants (MAIS = 3,4,5,6) of light trucks/vans are only 0.85% of all injured light truck occupants (MAIS not 0). Thus, in rollover crashes, light truck/van occupants (2.5%) have lower serious injury rate than car occupants (4.2%). This injury severity difference may possibly be due to smaller head room in cars compared with light truck/vans, meaning that the occupant head and /or neck may be more likely injured from contacting the roof in a car. Occupant contacts and injury sources will be examined using CDS data in a subsequent section of this study. The difference between roof designs and roof strengths associated with car and light truck/van may also contribute to the occupant injury severities, [2, 5] and more future research may shed a light on this challenging topic.

4.2 Rollovers and Ejection Areas of Light Passenger Vehicle Occupants

Since 2009, CDS data collected the crashes from vehicle age<=10 only, hence, the sample sizes could be smaller after 2008. [8] Figure 6 provides yearly trends of occupant injuries (MAIS 2-7) including all vehicle ages and vehicle age <=10 years old, respectively. This study also focuses on the crash data of recent years, 2013-2015.

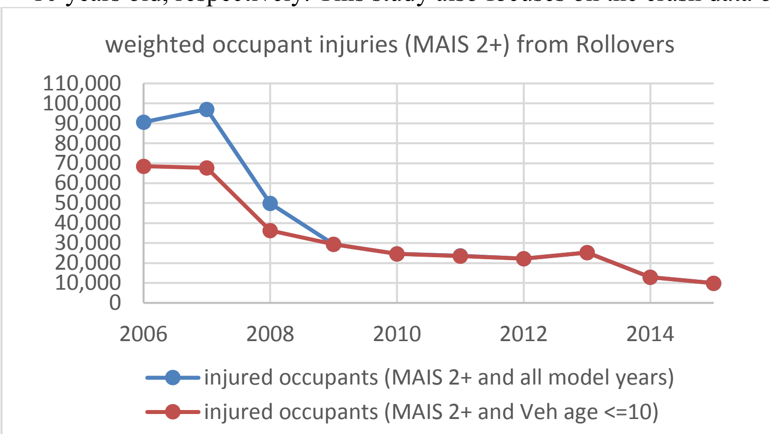

Figure 6: *Weighted occupant injuries (MAIS 2+) related to rollovers (CDS 2006-2015 light passenger vehicles including all model years, and vehicle age <=10, respectively)*

As discussed previously, rollovers are usually associated with occupant ejections. Figure 7 shows annual averages of ejection areas related to rollovers (CDS 2013-2015 including all vehicle model years and occupant injury levels). Occupants were more frequently ejected from the front side windows (left or right) and roof opening. In CDS 'OA' data file, there are four variables that are insightful to rollover and ejection details - 'ejection' (partial or full ejection status), 'ejection area' (windshield, left or right front, or roof, and 'ejection area' in CDS data is similar to the variable of 'ejection path' in FARS data), 'ejection medium' (non-fixed roof, fixed or non-fixed glazing, or integral structure), and 'entrapment' (entrapped or not, jammed door/fire). [20, 21] This paper will not include all related data explorations due to the paper size limit. All CDS data analysis included the occupants who were within the rolled vehicles or ejected, only Table 6 focused on the ejected occupants of rolled vehicles. Also, the CDS analytical results including AIS2+ could have much larger sample sizes than the similar results including AIS 3+ only, and the missing or unknown AIS, ejection status, and several key variables are still commonplace.

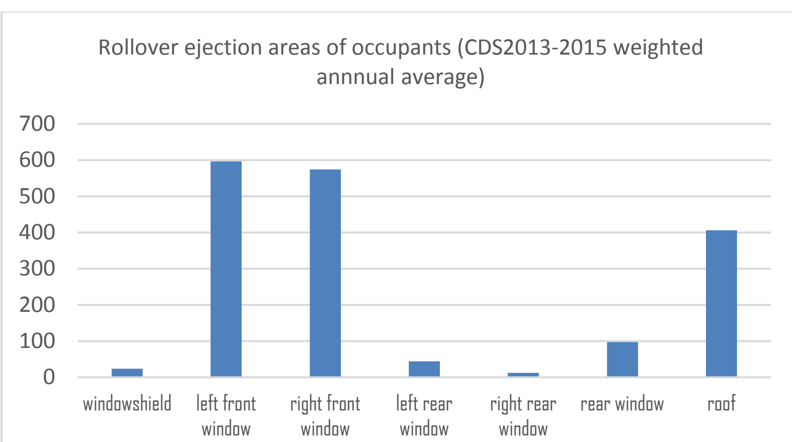

Figure 7: *Annual weighted average of ejection areas related to rollovers (CDS 2013-2015 light passenger vehicles with all model years)*

4.3 Injured Body Regions and Vehicle Contacts Related to Rollovers

When occupants are involved in rollover crashes, they are most frequently injured in the body regions of head, neck, and chest.[2, 3] CDS data of Occupant Injury (OI) contain very detailed descriptions of injured body regions and injury contact sources of vehicle components. Again AIS, a numerical scale system by AAAM to rate the injury severity, is used here to describe the injured body regions. 'OI' data file is merged together with general vehicle (GV) and occupant assessment (OA) data especially during 2013-15 (Figure 1). This study intends to explore several questions about rollover crashes and related injuries: one question may be what are the commonly injured body regions (head, face, chest or others)? What are common injury sources of vehicle components (e.g., roof, door, B-pillar) that contact the occupant in rollovers?

For rollover crashes (including vehicle age <=10 years old), the main injured body regions (AIS 2+) are head, chest, shoulder and back, and neck (Figure 8).

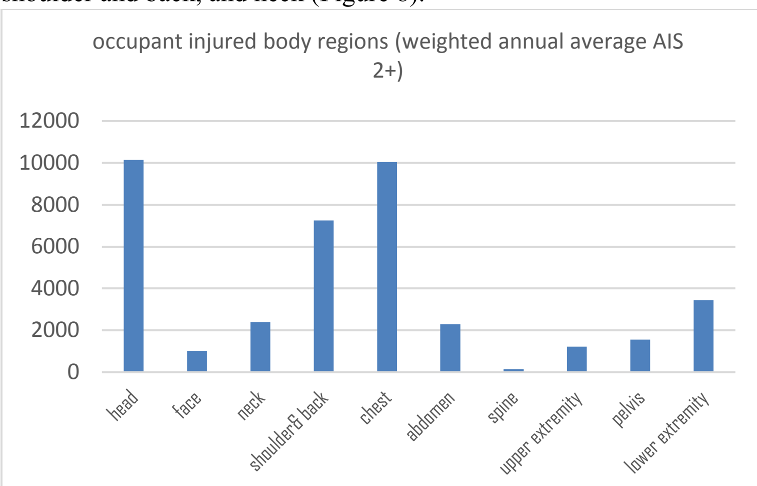

Figure 8: *Annual weighted average of injured body regions (AIS 2+) due to rollovers (vehicle age <=10 years, CDS 2013-2015)*

When a vehicle is involved in a rollover crash, some vehicle components are more likely to contact the occupants (driver and passenger), and these vehicle components become so called 'injury contact sources'. The main injury sources associated with AIS 2+ injuries in rollover crashes are roof, left side door/interior, instrument panel and seat back, as indicated by Figure 9.

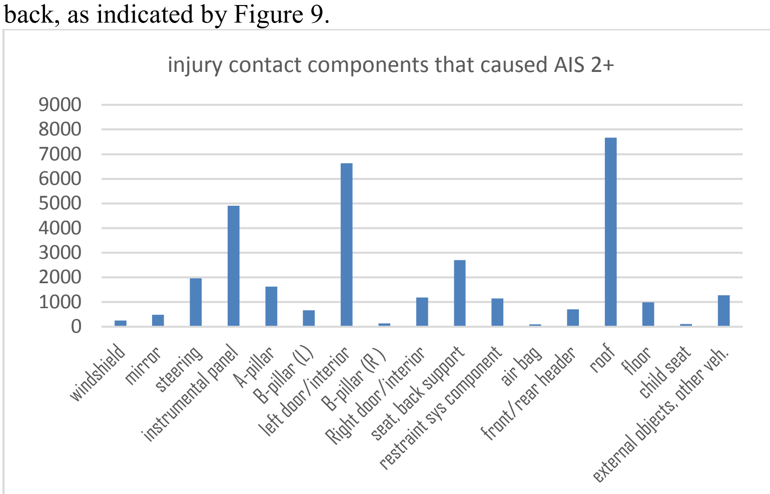

Figure 9: *Annual weighted average of injury vehicle component sources that caused AIS 2+ from rollovers (vehicle age <=10 years), CDS 2013-2015*

4.4 Injured Body Regions by Roof Contact Only Associated with Rollover

Injuries caused by the interaction between occupants and the vehicle roof only, when rollovers occurred, are of special interest in this study. Figure 10 shows the weighted average of injured regions, especially three body regions of head, neck, and shoulder /back, due to contacting the roof during rollovers (vehicle age <=10 years and AIS 2+, CDS 2013-2015). The interaction odds between the roof and head were especially high if a rollover crash did occur.

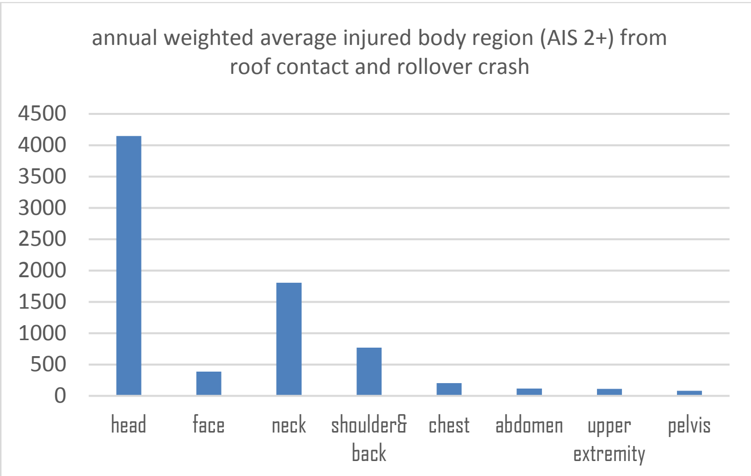

Figure 10: *Annual weighted average of injured regions due to contacting roof only of rolled vehicles (vehicle age <=10 years and AIS 2+, CDS 2013-2015)*

If additional years are included and CDS 2006-2015 data are used, Figure 11 shows that if the roof was the injury source and rollover occurred, the main injured body regions are head, neck, shoulder/back, and face. CDS 2006-2015 data provide a yearly trend of roof caused injured body regions when the vehicles were involved in rollover, where vehicle age, determined by (crash year – model year), is limited not more than ten years old. The weighted annual averages of injured body regions were lower during 2013-2015 than the similar averages of 2006-2009. This study also explored AIS results related to rollovers /ejections with vehicle age under 3-4 years only, but the sample sizes were small especially during 2011-2015 (not listed in this study).

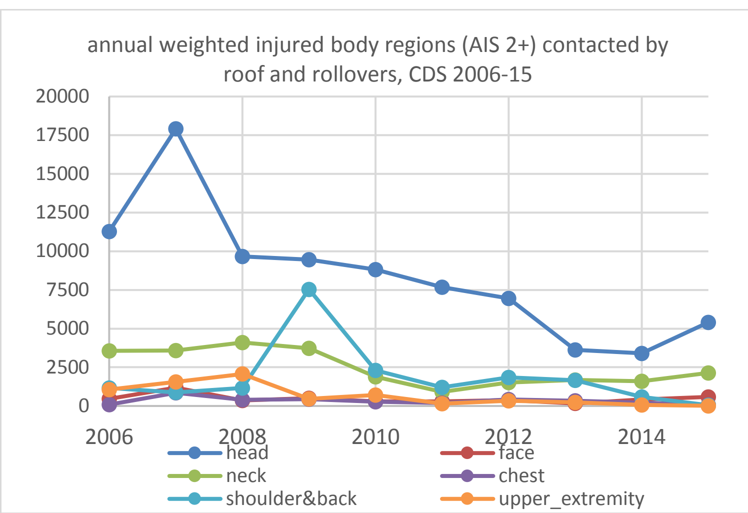

Figure 11: *Annual weighted injured body regions (AIS 2+) related to rollover crashes and roof contact only (vehicle age <=10 years, CDS 2006-15)*

5. ANNUAL TREND OF ROLLOVER INJURIES AND MULTIPLE RISKS

This section explored the yearly trends of rollover-related occupant injuries using CDS 2006-2015. In this trend analysis, MAIS is used to describe the overall maximum severity injury sustained by an occupant during 10-year span. Then a more general correlation investigation of occupant injuries is done by a multiple regression approach, when various risk factors, including rollover, side or longitudinal impact, delta-V, occupant age and belt use, are considered, simultaneously.

5.1 Occupant Injury Yearly Trend from Rollovers

The injured occupants involved in the rollover crashes per year, using MAIS versus calendar year during ten years (CDS 2006-2015), is shown as Table 5 and Figure 12, where only vehicle ages <=10 years old are included. It can be observed that the weighted injured occupants decrease after 2009, the injured occupant number could be even smaller, if only newer vehicles of vehicle ages not older than 4, or 2 years old are included.

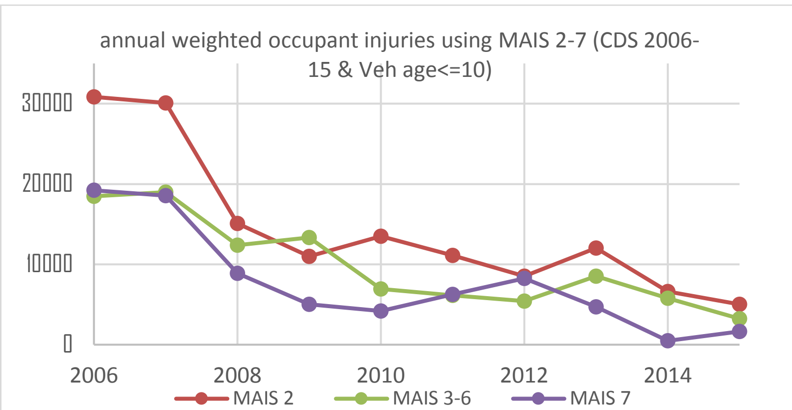

Figure 12: *Annual weighted occupant injuries (MAIS) related to rollovers crashes (CDS 2006-2015 including vehicle age <=10 years only)*

Table 5: *Weighted annual averages of occupant MAIS from rollovers crashes (CDS 2006-15 including vehicle age <=10 years only)*

YEAR	MAIS 1	MAIS 2	MAIS 3-6	MAIS 7
2006	102,036	30,839	18,478	19,210
2007	132,423	30,069	18,984	18,568
2008	125,774	15,106	12,383	8,873
2009	58,890	10,989	13,342	5,043
2010	54,688	13,515	6,916	4,174
2011	38,965	11,128	6,144	6,273
2012	35,849	8,529	5,439	8,235
2013	35,557	12,022	8,529	4,694
2014	71,256	6,622	5,776	483
2015	25,684	5,021	3,237	1,626

Table 6: *annual weighted injuries (MAIS) of both "rolled vehicle and ejected occupant" (CDS 2006-15 and vehicle age <=10 years only)*

YEAR	MAIS 1	MAIS 2	MAIS 3-6	MAIS 7
2006	2022	3325	9159	1996
2007	4751	2930	8412	1835
2008	3416	4409	4868	344
2009	2469	1118	3682	409
2010	2256	1746	2852	300
2011	301	722	2462	169
2012	595	504	1406	118
2013	350	521	1997	252
2014	966	186	331	93
2015	69	678	970	709

Table 5 provides the annual weighted occupant MAIS results including vehicle age <=10 years old. If newer vehicle models are preferred with the consideration of FMVSS 216a and 226, the similar occupant MAIS tables, including vehicle age <=4, and <=2 years old, respectively, are listed in Table 5b and 5c in Appendix.

Occupants involved in a rollover crash, and who were also ejected, are shown in Table 6 (with much fewer occupants than Table 5), and Table 6 provides MAIS for each year (CDS 2006-15, and vehicle ages<=10 years old). The ejection rates of occupants of rolled vehicles were related to their MAIS levels: the MAIS 3-6 group had the highest ejection rate of 36% approximately, the ejection rate for MAIS 2 was 11% approximately, while MAIS 1 had the lower rate of 2.5% (from Tables 5, 6).

Furthermore, if rollover crashes occurred, following Figures 13-14 show the annual injured occupant body regions (AIS 2+) using weighted CDS data during 2006-2015. It can be observed that head and shoulder /back injuries are most frequent, together with other injured body regions of face, neck, chest, upper and lower extremity areas.

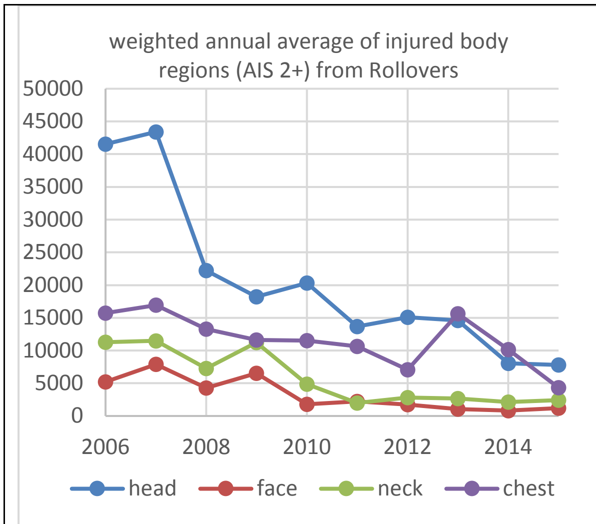

Figure 13: *Annual weighted average of injured body regions (AIS 2+) related to rollover crashes (vehicle age <=10 years, CDS 2006-2015)*

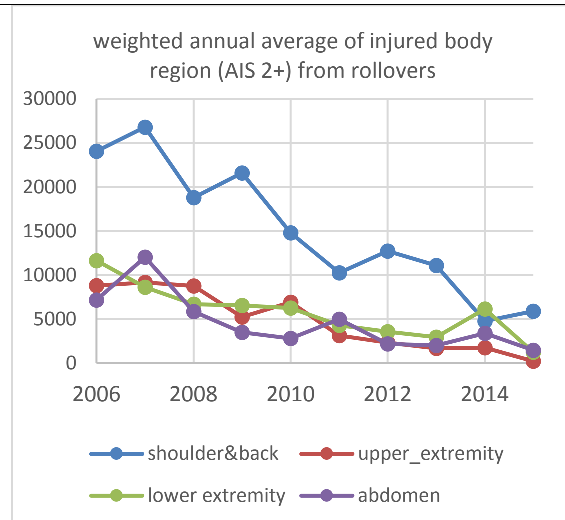

Figure 14: *Annual weighted injured body regions (AIS 2+) related to rollover crashes (vehicle age <=10 years, CDS 2006-2015)*

5.2 Occupant Injury Modeling with Consideration of Multiple Risks Simultaneously

The goal here is to establish a correlation between the occupant injuries (the outcome) and some contributing risk factors (the independent variables). The risk factors may include various crash types (rollover, side or longitudinal impact), delta-V, belt use and others. Many risk factors contribute to occupant injuries simultaneously, and some factors are more significant than others. Most CDS data are categorical data and are convenient to use for logistic regression. The logit model explores the relative risk of two different crash conditions and the impact from each risk factor on occupant injury severities. Some variables in CDS can be treated as binary data, e.g., injured body regions of AIS being '3, 4, 5, 6' were treated as 'serious and fatal injury' case (or '1', dependent variable), while AIS (0, 1, 2, 7) as not-serious case (or '0', dependent variable). Similarly, the common independent factors in the logit model include 'rollovers, or 1' vs. 'not-rollover, or 0', front seating occupant vs. rear-seating, side impact vs. frontal crash. This study also explored the effect of vehicle age on occupant injuries, and vehicle age is determined by (crash year – model year). The regression modeling intended to consider the impacts on occupant injuries from main risk factors, although not all factors can practically be included in this modeling. The modeling data came from CDS 2006-15, including any crash types, all AIS levels, and vehicle age <=10 years.

Several references provide excellent introduction to logistic regression and categorical data analysis.[13,14,17] Statistical correlation between the outcome and the independent variables is described as Eq. (2), from this correlation modeling it is possible to compare the occupant injury severity odds ratios (OR) between two very different crash conditions – for example, these include comparing the effects between rollovers versus not-rollovers; higher Delta-V (>35 MPH) versus lower delta-V; 'not-belted' occupants versus 'belted' occupants; furthermore, to compare side crashed vehicle with frontal crashed one; to compare smaller vehicle size (<3,000 lbs.) with the relatively larger sizes; or to compare older occupant (>65 years old) vs. the younger. This multiple regression model considers the effects of these primary eight risk effects on occupant injuries, simultaneously, as Eq. (2):

$$\ln(\frac{p}{1-p}) = \beta_0 + \beta_1 VehAge + \beta_2 DeltaV + \beta_3 VehSize + \beta_4 Belt + \beta_5 Rollover + \beta_6 DamageArea + \beta_7 Seating + \beta_8 OccupAge \quad (2)$$

In Eq. (2), '*ln*' is the natural log sign, 'p' is the probability of 'occupant serious injury (AIS =3,4,5,6)', and '$\frac{p}{1-p}$' is the odds of 'occupant serious injury' versus 'not serious injury'. This statistical modeling, using SAS procedure of '*SurveyLogistic*' [16, 17] that considers the PSU and sampling weights, provides the serious injury odds ratio (OR) results from eight risk factors, as summarized in Figure 15 and Table 7. Missing data are included and SAS procedures usually handle the missing data reasonably well. The large percentage of unknown or missing AIS could make it challenging to build a correlation model. The receiver operating characteristic (ROC) curve is used to give a measure of the predictive accuracy of a logistic regression model, and ROC curve displays the sensitivity and specificity of the model. The area under the ROC curve, measured by 'c statistic', is still relatively low (0.68), and future correlation modeling of using more complete AIS information and with more than eight independent risk factors in Eq. (2) may be desired.

Data Interpretation of Table 7 or Figure 15:
Results indicate that higher occupant serious injury risks are significantly associated with rollover crashes, OR=1.74 (95% confidence interval 1.31 to 2.31, with a significant p-value of 0.0001), e.g., the occupants of rollover vehicles would be 74% more likely seriously injured (AIS 3+) when compared with the occupants of not-rolled vehicles. Similarly, higher injury risk is associated with higher delta-V (>35 MPH, OR=5.59), 'not-belted' (OR=3.26, 95% confidence interval 2.63 to 4.04), side crash (OR=1.54), and older occupant age (OR=2.69). On the other hand, older vehicles (>4 years), seating row, and smaller vehicle size (under 3,000 lbs.) did not have significant impact on occupant injuries (with p-values more than 0.05). Figure 15 clearly indicates that three highest risk factors come from higher Delta-V >35 MPH (driving speed or crash severity), 'not using belt , and old occupants, and rollover crash is also a significant risk factor.

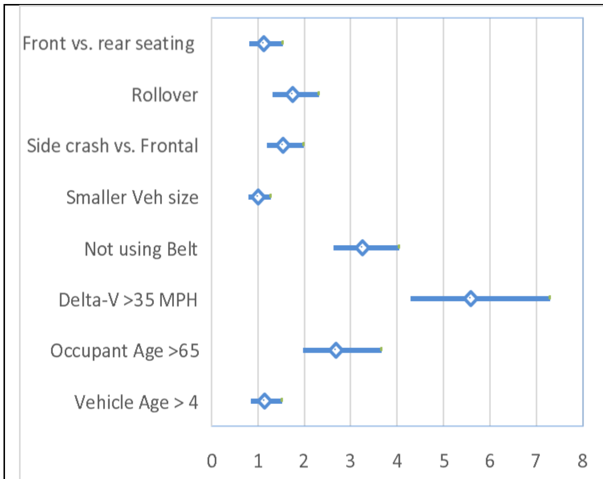

Figure 15: *Odds Ratios (Means and 95% Confidence Intervals) of Occupant Serious Injury (AIS 3+), including several risks simultaneously (CDS 2006-15 vehicle age <=10)*

Table 7*: Odds Ratios (means and 95% Confidence Intervals) of Occupant Serious Injuries (CDS 2006-2015 including vehicle age <=10)*

Effect	Point Estimate	95% Wald Confidence Limits		p-Value
Vehicle Age > 4	1.136	0.849	1.522	0.3910
Occupant Age >65	2.686	1.969	3.664	<.0001
Delta-V >35 MPH	5.591	4.282	7.299	<.0001
Not using Belt	3.257	2.625	4.041	<.0001
Smaller veh size	1.004	0.788	1.279	0.9748
Side impact vs. Frontal crash	1.543	1.197	1.990	0.0008
Rollover	1.740	1.308	2.314	0.0001
Front vs. rear seating	1.123	0.815	1.546	0.4778

6. CONCLUSIONS AND DISCUSSIONS

FARS and CDS data systems were used to explore the occupant injuries related to vehicle rollover crashes and occupant ejections, while GES vehicle data could also be used as a reference to CDS data. This data analysis used a simple approach of 'step-by-step' approach – e.g., from annual occupant fatalities in FARS data to the vehicles involved in rollovers in both GES and CDS data; from the rollover-related occupant injuries with overall MAIS to the detailed injured body regions (AIS) and injury contact sources (roof or side doors). Finally, this study viewed occupant injuries from a bigger picture by considering multiple risk factors simultaneously. Some key findings from this study are –

- The FARS data indicated annual rollover-caused fatalities decreased from around 10,500 in 2004-2006 to approximate 7,000 in 2014-2017, approximately one thirds of all occupant fatalities of light passenger vehicles are from rollover crashes, but the percentage of rollover-related occupant fatalities among all occupant fatalities dropped sharply during 2011-2017. The number of both rollover and ejection-caused fatalities decreased from approximately 6,000 in 2004-2006 to 3,600 in 2014-2017. The occupant fatalities associated with various known ejection paths (e.g., side windows, roof, etc.) were approximately 15% of rollover-related occupant fatalities.

- CDS 2013-2015 weighted survey data showed approximately 161,000 light vehicles (cars and light trucks/vans, GVWR <=10,000 lbs.) were involved in rollovers (similarly, GES data were also used to estimate the rolled vehicles), and approximately 190,000 occupants of light passenger vehicles were injured (MAIS 1+) annually related to rollovers.
- Rollover crashes tend to be more likely associated with light trucks/vans than passenger cars, and this may be possibly due to higher centers of gravity in light trucks, however, if rollovers did occur, the passenger car occupants were more likely to be seriously injured (MAIS =3,4,5,6) than the light truck/van occupants.
- The CDS data indicated that rollover injuries (especially AIS 2+) were strongly associated with the injury sources of the vehicle roof, side doors, instrumental panes, and seat back/support; and rollover crashes also resulted in primarily the injured body regions of head, shoulder/back, neck, and chest.
- When a rollover crash occurred, contact between occupant and roof primarily caused head injury, as well as neck and shoulder/back injuries.
- The ejection rates of occupants of rolled vehicles were significantly related to their MAIS levels from CDS 2006-15: the MAIS 3-6 group had the highest ejection rate of 36% approximately, the ejection rate for MAIS 2 was 11%, while MAIS 1 group had the lower rate of 2.5%.
- A multiple logit regression was used, with considerations of all crash types and multiple risk factors simultaneously, to predict the occupant injury relative risks of several risk factors, e.g., comparing rollover versus not-rollover, belted occupants versus not-belted, higher delta-V versus lower. It was found that higher occupant injury risks are significantly associated with rollover crash (OR=1.74), delta-V >35 MPH (OR=5.59), not-belted (OR=3.26), side impacts (OR=1.54), and older occupant age >65 (OR=2.69). On the other hand, older vehicles (>4 years), seating position, and relatively smaller vehicle size did not have significant impact on occupant injuries with p-values > 0.05.
- This study paid close attention to data structures and data sorting, data appending vertically and data merging horizontally, logic design of flow-chart, and vehicle crash type identifications using key research variables.
- With consideration of FMVSS 216a and 226 that focused on the newer vehicles after 2011, this study explored the effect of vehicle age and focuses on the recent crash data (CDS 2013-15), the rollover-related occupant injuries, including vehicle age <=2, <=4, and <=10 years old, respectively, are listed, but CDS database is still limited by the sample size, especially if only model years after 2011 are included.
- CDS data analysis is also limited by the high percentages of missing or unknown values of some key variables, such as delta-V, rollover/ejection status, and AIS.
- Overall, this study may enrich the understanding of rollover crashes, ejections and occupant injuries from using recent crash data. Future data analysis, using both NASS Crash Investigation Sampling System (CISS) and Crash Reporting Sampling System (CRSS) data starting since 2016 that are collected from more PSU, may provide more insights of rollover crashes, ejections, and occupant injuries.

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9. APPENDIX

Table 5b: *Weighted annual averages of occupant MAIS from rollovers crashes (CDS 2006-15, vehicle age <=4)*

YEAR	MAIS 1	MAIS 2	MAIS 3-6	MAIS 7
2006	35,197	5,180	6,932	6,209
2007	41,239	12,146	6,574	3,043
2008	72,017	7,004	6,217	4,264
2009	18,981	3,102	3,514	591
2010	27,901	3,819	2,349	1,661
2011	16,133	4,064	1,893	546
2012	17,195	3,250	1,998	1,049
2013	9,075	4,287	4,569	2,627
2014	17,540	3,108	1,390	352
2015	15,997	2,998	899	1,007

Table 5c: *Weighted annual averages of occupant MAIS from rollovers crashes (CDS 2006-15, vehicle age <=2)*

YEAR	MAIS 1	MAIS 2	MAIS 3-6	MAIS 7
2006	18,151	2,493	3,245	4,641
2007	23,664	5,894	3,067	955
2008	14,541	2,510	3,642	2,846
2009	7,828	1,611	1,336	314
2010	16,144	2,850	1,409	1,229
2011	8,168	2,148	1,082	395
2012	11,692	1,004	1,132	726
2013	3,319	2,947	1,483	1,423
2014	12,855	1,395	832	352
2015	6,505	1,003	554	666