Seat belt design and risk of injury in rollover crashes: a comparison of conventional and seat-integrated restraints

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A thesis
submitted in partial fulfillment of the
requirements for the degree of

Master of Public Health

University of Washington
2013

Committee:
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Program Authorized to Offer Degree:
Epidemiology

University of Washington

Abstract

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Background: Passenger vehicles in the United States currently utilize two seat belt designs: frame-mounted ("conventional restraints"; most common) and seat-mounted ("seat-integrated restraints.") The relative risk of injury in relation to seat belt configuration is unknown. **Methods:** The National Automotive Sampling System (NASS) Crashworthiness Data System (CDS) provided detailed information for a representative sampling of motor vehicle crashes in the United States. Modified Poisson regression was used to compare the risk of moderate or severe injury (Abbreviated Injury Scale (AIS) ≥2) for seat-integrated restraints relative to conventional restraints. **Results:** After adjustment for vehicle model year and vehicle type, the relative risk of moderate or severe injury associated with seat-integrated restraints was 1.47 (95% Confidence Interval (CI) 0.95 to 2.26). The relative risk of moderate or severe head or neck injuries associated with seat-integrated restraints was 2.09 (95% CI 1.05 to 4.15). **Discussion:**

Seat-integrated restraints were associated with a statistically significantly higher risk of moderate or severe head or neck injury, and a non-significant yet elevated risk of moderate or severe overall injury. In light of known performance limitations of seat-integrated restraints in other types of crashes, lack of evidence for a protective effect of seat-integrated restraints may be cause to re-evaluate their utility.

Introduction

Motor vehicle collision (MVC) injuries remain an important cause of death in the United States. Vehicle rollovers are associated with a particularly increased risk of occupant injury. Rollover crashes represent only 3% of the nation's crashes yet cause approximately one-third of all vehicle occupant fatalities.(1) Although seat belts are well known to reduce injury risk in a rollover MVC,(2) potential differences in the effectiveness of current seat belt designs have not been fully examined.

In 2010, unintentional injuries were the fifth leading cause of death in the United States and motor vehicle-related injuries represented 28% of total injury mortality, resulting in 33,000 deaths.(3) Rollover crashes were among the most deadly forms of passenger vehicle MVC, resulting in 7,659 fatalities in 2010.(4) Although the overall passenger vehicle occupant fatality rate for rollover crashes has dropped markedly from 4.89 per 100,000 registered vehicles in 2001 to 3.22 in 2010, the rate for the light truck category (comprising SUVs, pickups, and vans) remains more than double that of passenger cars (4.64 vs. 2.15 per 100,000 registered vehicles in 2010).(4) Light trucks involved in fatal crashes are roughly twice as likely to have rolled over compared to passenger cars (36% vs. 18% of fatal crashes).(5) As the number of rollover-prone light trucks on the road increases,(4) there is a need for further research on rollover-specific injury prevention strategies.

Many risk factors for morbidity and mortality in rollover crashes have been identified. Occupant ejection, non-use of seat belts, increased number of roof impacts, and older occupant age were all significantly associated with risk of fatal, serious, head, and cervical spine injuries in rollover crashes.(6) Seat position in relation to the direction of the rollover is associated with risk of death; occupants seated in the "outside arc" of the roll are more likely to sustain fatal

injuries.(7) One factor that is not well understood, however, is whether any difference in risk exists between the two seat belt designs currently in use.

Two styles of seat belt restraints have been used in most personal vehicles in the United States since the 1990s.(8) Most commonly, seat belts are mounted to the vehicle frame and comprise both a shoulder belt and a lap belt. These restraint systems are referred to as conventional restraints. Some vehicles, however, contain seat belts that are integrated into the vehicle's seat. This design, commonly referred to as a seat-integrated restraint system, belt-in-seat system, or all-belts-to-seat system, has been hypothesized to perform better in rollover crashes due to its closer proximity to the passenger's body, purportedly resulting in superior movement restriction in the event of a crash.(9) This, however, has not been fully investigated. Seat-integrated restraints are further hypothesized to provide additional protection against the risk of head and neck injuries in vehicle rollovers by restricting vertical movement of the occupant's torso, thereby reducing the likelihood of occupant contact with the vehicle roof.

Our primary aim was to examine the role of seat-integrated restraints relative to conventional restraints in rollover crash-related injuries using the National Automotive Sampling System (NASS) Crashworthiness Data System (CDS), a nationally representative sample of MVC with injury outcomes determined by trained investigators. Secondary outcomes examined in this study included injuries to the head and neck. Rollover crashes have a much greater risk of head and neck-related injuries compared to other types of MVC and these injuries carry a disproportionate burden of morbidity and mortality.(10)

Methods

Overview

A retrospective cohort design was used to examine the association between seat restraint type and risk of moderate or severe injury among vehicle occupants involved in rollover crashes documented in NASS CDS during the years 2002-2011. The National Highway Traffic Safety Administration compiles the NASS dataset, a nationally representative sample of police-reported motor vehicle crashes that required at least one vehicle involved in the crash to be towed from the scene due to damage.(11) The CDS component of NASS collects additional data, including crash characteristics (e.g. sequence of crash events, rollover severity), vehicle characteristics (e.g. make, model, year), occupant characteristics (e.g. age, height, seating position, seat belt use) and occupant injuries (e.g. injury severity, body region affected). This information is obtained from police reports, medical records, interviews with emergency medical services personnel, and coroner and autopsy reports. Data are collected at 24 sampling sites across the United States; approximately 5,000 new events are included in the database each year.

Sample

Front seat occupants of vehicles involved in a rollover crash (designated by the occurrence of at least one quarter-turn revolution of the vehicle) were identified from the 2002-2011 NASS CDS datasets. The analysis was limited to front seat occupants, who are at greatest risk of injury in rollover crashes. (12) Only occupants seated in the front left (driver) or front right (passenger) seat positions were included. Occupants were restricted to individuals aged 13 years and older based on findings of increased risk of injury for children aged 12 or younger when seated in the front seat and current NHTSA recommendations that children younger than 13-years-old ride in the rear seats of vehicles.(13,14) Unbelted occupants and those wearing lap-only or shoulder-only restraints were also excluded.

In 2009, NASS CDS investigators ceased detailed data collection of vehicle and occupant characteristics for vehicles more than ten years old. To maintain consistency across years of data, occupants of vehicles older than ten years at the time of the crash were excluded from the analysis. A total of 4,425 adult, belted, front-seat vehicle occupants in rollover crashes were eligible for inclusion in the analysis. Missing injury or restraint data eliminated approximately 11% of the sample: out of the 4,425 occupants, 229 (5.18%) were missing maximum AIS, 235 (5.31%) were missing restraint type and 6 (0.14%) were missing data for both variables. The resulting analysis set of 3,955 occupants represented a national crash set of 1.44 million occupants.

Variable definitions

Occupants using seat-integrated restraints were considered as "exposed"; those using conventional restraints were considered "unexposed". This information was captured in the CDS occupant assessment dataset for 2010-2011 and in the supplemental SeatLoc tables for 2002-2009. The primary outcome of interest was the occurrence of moderate or severe injury defined as a maximum AIS ≥2. The secondary outcome of interest was the occurrence of moderate or severe injury to the head or neck (AIS ≥2 for body region head or neck). Maximum AIS was identified from the occupant assessment dataset. AIS codes derived from the 1990-Update 98 version of the AIS coding manual(15) were used for consistency in AIS coding across years of data (CDS began using the AIS 2005-Update 2008 manual in 2010).(11)

Potentially confounding factors evaluated included the vehicle type (passenger car, pickup, SUV, van) and vehicle model year. These two factors are causally associated with both the restraint type and the risk of rollover crash injury.(4,8) Many other factors are associated

with rollover crash injury, such as advanced occupant age,(16) ejection status,(2) and vehicle speed, (6) but not with seat belt type. Following the guidelines of Greenland et al., factors associated with rollover crash injury but not seat belt type were not included in the model to avoid introducing possible confounding.(17) Potential effect modification by rollover crash severity was examined by testing the inclusion of an interaction term between seat belt type and number of roof impacts to the rolled vehicle (0, 1, or ≥ 2 impacts). Number of roof impacts was defined using the number of quarter-turns of the vehicle (a single quarter-turn of the vehicle was categorized as 0 roof impacts, 2-5 quarter-turns as 1 roof impact, and 6 or more quarter-turns as ≥ 2 roof impacts). Occupant seated in the "outside arc" were identified using the NASS CDS variable for rollover direction and defined as the occupants seated in the front left seat of vehicles that rolled to the right and occupants seated in the front right seat of vehicles that rolled to the left.(7)

Analysis

Analysis was conducted using multiple robust Poisson regression. Although the outcomes of interest in this study were binary, robust Poisson regression is an alternative to logistic regression when the outcome is common.(18) The *svy* family of commands in Stata was used to account for the complex sampling design of NASS CDS that involves stratification and multiple levels of clustered data. (19) The use of Stata *svy* commands in conjunction with NASS CDS sampling weights provided a risk ratio estimate representative of all police-reported crashes nationally with unbiased variance estimators. All percentages reported are weighted estimates except where otherwise noted. Adjusted risk ratios for the association between restraint type and risk of moderate or severe injury were calculated with 95% confidence intervals (CI) using Stata version 12 (StataCorp, College Station, TX). Exploratory analyses estimated adjusted risk ratios

for three categories of roof impacts to the vehicle and for occupants seated in the "outside arc." As publicly available data were used, this project was exempt from institutional review.

Results

There were 3,955 adult, belted, front-seat occupants involved in rollover crashes who also had a maximum AIS recorded by NASS CDS investigators. 355 occupants (9.0%) had used seat-integrated restraints and 3,600 (91.0%) had used conventional restraints (Table 1). Of the front seat occupants involved in rollover crashes, 5.5% were using seat-integrated restraints nationally, while the remaining 94.5% were using conventional restraints. The majority of occupants in both seat belt categories were male (61.9% of seat-integrated restraint wearers, 57.7% of conventional restraint wearers). Occupants of vehicles with seat-integrated restraints were generally somewhat older than occupants with conventional restraints (mean age 39.3 vs. 31.6 years).

Occupants wearing seat-integrated restraints were more likely to be riding in SUVs and pickup trucks, whereas occupants wearing conventional restraints were more likely to be riding in passenger cars and SUVs. Only 2.2% of the seat-integrated restraint occupants were riding in a passenger car, compared to 37.2% of the conventional restraint occupants. Vehicle model year varied somewhat by belt configuration: 30.9% of occupants wearing conventional restraints were riding in 1993-1999 vehicles, compared to 5.3% of occupants with seat-integrated restraints. The great majority of seat-integrated restraint occupants were from 2000-2006 models (92.1% compared to 63.1% for conventional restraints).

Most of the crashes in both groups involved two to five quarter-turns or an end-over-end crash, both of which were categorized as a single roof impact. Occupants wearing seat-integrated

restraints were more likely to have been in more serious rollover crashes. Nearly 17% of occupants wearing seat-integrated restraints were involved in crashes with 2 or more roof impacts compared to 8.8% of conventionally restrained occupants.

In the study sample, 84 of 355 (23.7%) individuals wearing seat-integrated restraints suffered an injury rated as AIS $\geq$ 2 (Table 2). 1052 of 3600 (29.2%) individuals wearing conventional restraints incurred such an injury. After application of sampling weights, however, moderate injuries were observed in 13.18% of seat-integrated restraint occupants and 9.28% of conventional restraint occupants. Seat-integrated restraints were associated with a non-statistically significant 47% higher risk of moderate or severe injury (adjusted risk ratio (aRR) 1.47, 95% CI 0.95 to 2.26, p=0.08). Moderate or severe head or neck injuries were more than twice as likely for occupants wearing seat-integrated restraints as those wearing conventional restraints (aRR 2.09, 95% CI 1.05 to 4.15, p=0.04).

Though lacking in power, an exploratory analysis was carried out to examine adjusted risk ratios for three categories of crash severity as measured by the number of roof impacts incurred by the rolling vehicle (Table 2). No linear trend was present: the risk of moderate or severe injury associated with seat-integrated restraints was 14% higher in crashes without a roof impact, 63% higher in crashes with a single roof impact, and 31% lower in crashes involving two or more roof impacts. None of these estimates for overall moderate or severe injury was statistically significant. Occupants wearing seat-integrated restraints had a higher, but non-statistically significant, risk of injury to the head or neck body regions in crashes with no roof impacts and those with two or more roof impacts. A statistically significant difference was found for crashes with a single roof impact, with occupants wearing seat-integrated restraints estimated

to be at 2.6 times greater risk of head or neck injury compared to occupants wearing conventional restraints (aRR 2.60, 95% CI 1.35 to 5.00, p=0.01).

Discussion

Our results are suggestive of a possible increased risk of overall moderate or severe injury with the use of seat-integrated relative to conventional restraints, however, in the multivariable model, these results were only marginally significant. This is in contrary to previous hypotheses that seat-integrated restraints are protective of injury in rollover crashes. A statistically significantly increased risk of moderate or severe head or neck injury was estimated for seat-integrated restraints relative to conventional restraints.

In a previous analysis of police-reported injury outcomes from 1991-2004, no statistically significant difference in fatal or fatal/serious injury rates was identified between these two types of restraint systems.(8) Our results are somewhat consistent with this finding, in that our risk ratio estimates did not support the hypothesized protective effect of seat-integrated restraints. The researchers examined the more severe outcome of serious and fatal injury and relied on police-reported injury outcomes, a potential source of bias in their findings as police-reported outcomes have been found to be only moderately correlated with actual outcomes ascertained by trained investigators.(20) The present analysis contributes additional evidence questioning the effectiveness of seat-integrated restraints.

Findings from Jehle et al. established occupant seat position in the “outside arc” as a risk factor associated with injury or death among front seat occupants. Explanations of the increased risk associated with outside arc seating include greater roof crush and increased initial rotational torque.(7) The NASS CDS dataset provides the direction of roll for rollover crashes, which was

used to isolate a subpopulation of occupants who were seated in the outside arc. The relative risk of moderate or severe injury associated with seat-integrated restraints amongst outside arc occupants was comparable to that of all rollover occupants: a 43% higher risk (aRR 1.43, 95% CI 0.81 to 2.55) amongst outside arc occupants compared to 47% higher risk for all occupants. The risk of moderate or severe head or neck injuries was 52% higher (aRR 1.52, 95% CI 0.70 to 3.31) for outside arc occupants wearing seat-integrated restraints, whereas all rollover occupants wearing seat-integrated restraints were at approximately double the risk of conventional restraints. Despite the hypothesized benefits of seat-integrated restraints for restricting occupant movement due to initial rotational torque, occupant seat positioning in the outside arc of rollover crashes does not appear to modify the risk of moderate or severe injury associated with seat-integrated restraints.

Crashes in which occupants were wearing seat-integrated restraints were oversampled in the NASS CDS dataset. The mean sampling weight for these individuals was considerably less than the sampling weight for individuals wearing conventional restraints. Some analyses of NASS CDS data have used survey weights truncated at the 95th percentile, as researchers have found that increased variation in sampling weights may significantly widen the CI. (21) The main analysis in this paper did not adjust for this consideration. As an exploratory examination, we calculated risk estimates using survey weights truncated at the 95th percentile. With truncated survey weights, no statistically significant difference was seen in the risk of moderate or severe injury for occupants wearing seat-integrated restraints compared to conventional restraints (aRR 0.99, 95% CI 0.64 to 1.51). In this analysis, the reduced survey weight variation led to similarly wide confidence intervals but attenuated risk estimates for moderate or severe injury. The difference between the aRR calculated in our primary analysis and the aRR calculated using

truncated survey weights shows the extent to which risk estimates can be influenced by small numbers of sampled crashes that are weighted to represent many more crashes in national estimates. This is a potential source of bias, as any inaccuracies in the assumptions underlying NASS CDS-provided sample weights are magnified when nationally representative estimates are calculated.

Although seat-integrated restraints were hypothesized to be protective in rollover crashes, there is some evidence that they provide lesser protection in other types of crashes, particularly rear-impact crashes.(22) Sled tests simulating rear-impact crashes measured increased loads on the head and spine of dummies and greater risks of whiplash for dummies in seats with integrated restraints compared to those with conventional seats in the same vehicle model. (22) Among rear seats with integrated restraints, frontal rigid barrier crash tests have yielded evidence of greater forces for head or neck injury compared to seats with conventional restraints.(9) In light of the lack of protection afforded by seat-integrated restraints in rear-impact crashes and the increased risk of head and neck injuries measured in this study, there is little evidence supporting the continued manufacture of vehicles with seat-integrated restraints in the front seats.

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Table 1. Occupant and crash characteristics by restraint type

	Conventional Restraint	**Seat-integrated Restraint**
	N	N
Sample	3600	355
Population	1,355,999.6	79,053.5
	%	%
Sex		
Male	57.73	61.88
Female	42.27	38.12
Age, mean (sd)	31.59 (1.46)	39.26(1.16)
Age category		
13-29	57.54	36.12
30-59	36.32	48.75
60-96	6.14	15.13
Vehicle Type		
Passenger Car	37.16	2.20
Pickup Truck	21.16	46.20
SUV	34.83	49.40
Van	6.84	2.20
Vehicle model year, mean (sd)	2000.97(0.11)	2002.83(0.18)
Model year category		
1993-1999	30.84	5.29
2000-2006	63.08	92.08
2007-2012	6.07	2.63
AIS		
0-1	90.72	86.82
≥ 2	9.28	13.18
Roof Impacts		
0 (1 quarter-turn)	24.87	12.62
1 (2-5 quarter-turns)	66.29	70.41
≥ 2 (6 or more quarter-turns)	8.84	16.97

Table 2: Adjusted risk of moderate or severe injury with and without stratification on number of roof impacts

Variable	**Conventional Restraint**	**Seat-integrated Restraint**
AIS ≥ 2/occupants, No.		
Study Sample	1052/3600	84/355
National Set	125885.9 / 1355999.6	10419.0/79053.5
Crude AIS ≥ 2 Rate per 1000 occupants, National Set	92.8	131.8
Primary Analyses		
	Adjusted Risk Ratio*	**95% Confidence Interval**
Any AIS ≥ 2	1.47	0.95-2.26
Head/Neck Injury AIS ≥ 2	2.09	1.05-4.15**
Exploratory Analysis of Effect Modification by Number of Roof Impacts		
Any AIS ≥ 2		
0 Roof Impacts	1.14	0.15-8.53
1 Roof Impacts	1.63	0.94-2.85
≥ 2 Roof Impacts	0.69	0.28-1.72
Head/Neck Injury AIS ≥ 2		
0 Roof Impacts	1.90	0.23-15.92
1 Roof Impacts	2.60	1.35-5.00**
≥ 2 Roof Impacts	1.27	0.49-3.29
*Risk estimates adjusted for vehicle model year (continuous) and vehicle type (passenger car, SUV, pickup truck, or van) **p<0.05		