Performance Evaluation of Seat-Integrated Restraint Systems (SIRS) in Controlled Crashes

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Abstract Objective: Seat Integrated Restraint Systems (SIRS) were introduced in the 1990s and were most utilised in 1995 to 2010 model year vehicles. Few vehicles manufactured today are equipped with SIRS in the front seat, yet they are given serious considerations for future autonomous driving vehicles as they offer flexibility in seating orientation. This study assesses the safety performance of SIRS using U.S. field accident data. It evaluates whether SIRS affected seatbelt use and affected injury risks.

Method: 1995–2015 NASS-CDS and 2017–2022 CISS were analysed to assess the performance of SIRS by comparing the restraint use and the risk of serious-to-fatal injury (MAIS 3+F) for front outboard occupants [FOB) in integrated seats (SIRS) and in conventional seats (non-SIRS) of similar vehicles. The data was analysed by crash type and vehicle type. Except for restraint use, the analysis was limited to belted occupants 13 and older.

Results: Seatbelt use was similar in SIRS and non-SIRS, irrespective of vehicle type. Overall seatbelt use was 86.5% (95% CI: 84.1%–88.9%) in SIRS and 87.7% (95%CI: 85.5%–89.9%) in non-SIRS. The risk of serious injury was greater in SIRS than non-SIRS, irrespective of vehicle and crash types. Differences in injury risk however only reached statistical significance in frontal crashes with passenger cars with a risk of 3.31% (95%CI: 1.68%–5.80%) in SIRS and 1.18% (95^{th} CI: 0.64%–1.99%) in non-SIRS. The relative risk was 2.80 (1.31–6.00, p=0.002). It was marginally significant in frontal crashes with a relative risk of 1.60 (95%CI: 0.96–2.67, p=0.061). The survey-based logistic regression found that age, sex, front airbag deployment, and crash severity had a significant association with injury ($p<0.05$).

Conclusions: The evaluation of SIRS performance in the field indicates that they did not provide an overall safety advantage over conventional seats; they did not reduce injury risks nor encourage front seat occupants to use their seatbelt. Additional investigations of SIRS performance may be warranted prior to being considered for autonomous driving, including testing in various crash conditions.

Keywords integrated seat, injury, crashes, real-world data.

I. INTRODUCTION

Various seat designs have been proposed over the years, including seat integrated restraint systems (SIRS, also called ABTS – All Belts to Seat). SIRS have the shoulder belt anchored directly to the seatbacks such that the lap-shoulder belt is integrated into the seat structure. SIRS were first discussed in the 1960s to increase belt use [1] and facilitate rear seat ingress and egress [2]. SIRS were introduced in the 1990s and used primarily in vehicles without B-pillars, such as in convertibles and extended cab pickups. Front outboard SIRS were most utilised in 1995 to 2010 model year vehicles [3-5]. Most SIRS today are found in the second row because of lack of belt anchor, in particular in the centre seat. To our knowledge, no US vehicles are equipped with SIRS in the front seat today partly due to the lack of performance benefit combined with consumer preference for conventional belt systems, increased weight and packaging issues. Modern advanced seatbelt systems offer features that are difficult to implement with upper belt anchors used in SIRS. Advanced seatbelt features put in place to better control chest loading require a

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stable anchor that is not possible with a SIRS design. Nonetheless, SIRS are currently considered in the front seat for autonomous driving as they offer restraint flexibility in various seating orientations.

Jorlöv et al. [6] conducted a user-study for highly automated driving and concluded that front seats that rotated 180 degrees were the most preferred position. As a result, various researchers have been assessing occupant responses in rear-facing seat configurations in very high-speed frontal (up to 60 km/h) crashes using modified SIRS [7-11]. The results are used to potentially ensure that occupant protection on a rearward facing seat is comparable to a forward-facing conventional seat in regulated tests. Studies on the performance of forward-facing SIRS in rear impacts also provide valuable insight on injury type and risks.

The effectiveness of Seat Integrated Restraint Systems (SIRS) has been evaluated in comparison with conventional seats (non-SIRS) using rear impact test and field data. Viano and White [12] reported that SIRS were stronger in rear crashes than conventional seats because the seatback supports shoulder belt forces in frontal crashes and the anchorages must meet FMVSS 208 and 210 requirements. To assess the effect of increased seat strength, various laboratory tests were conducted in rear impacts to assess the biomechanical and kinematics responses of front-seat occupants in SIRS [13-15]. Parenteau et al. [16] summarised matched rear impact tests conducted with front-seat SIRS and non-SIRS and found higher overall biomechanical responses in SIRS irrespective of ATDs (Anthropometric Test Device), initial posture, and crash severity (delta V). Field data analyses were also conducted to compare SIRS and non-SIRS performance in rear impacts. Padmanaban et al. [17] investigated this issue using field accident data from various states in the US. They assessed injury risks for belted drivers in SIRS and non-SIRS seats in rear crashes and found that SIRS was not a statistically significant predictor of serious-to-fatal injury. This study updates the Padmanaban study using additional models and model years with SIRS as well as a more refined matching of SIRS and non-SIRS comparison model pairs. In addition, instead of field data from several US states, this study used a nationally representative sample of tow-away vehicles from two survey programs administered by the National Highway Traffic Safety Administration (NHTSA). Two hypotheses were evaluated. The first hypothesis consisted in evaluating whether SIRS affected belt use. The second hypothesis was to assess whether there was a safety advantage of SIRS compared to match paired non-SIRS seats in front and rear impact crashes.

II. METHODS

Data Sources

This analysis used field crash data compiled by the NHTSA. The Crashworthiness Data System (CDS) and its successor, the Crash Investigation Sampling System (CISS) are survey programs aiming at collecting a representative set of motor vehicle crashes, with some degree of severity, to provide reliable field data to support traffic policy and safety research. This data is publicly available. Because of the similarity of the two programs, analysts from NHTSA have demonstrated the feasibility of using multiple years of data from both programs, with some adjustments, to enhance statistical accuracy and precision in an analysis [18]. This study followed NHTSA's procedure for combining the CDS and CISS data. The specific years used in this study include the 1995–2015 CDS and the 2017–2022 CISS.

Vehicle Selection

Assessment of the performance of Seat Integrated Restraint Systems (SIRS) was conducted by comparing the injury risk of belted front outboard occupants in integrated seats and in conventional seats of similar vehicles. Injuries sustained during vehicle collisions have complex etiology involving occupant-related (e.g., age, sex), vehicle-related (e.g., airbag deployment, intrusions), and crash-related (e.g., crash type, crash severity) factors. To better isolate the safety performance of integrated seats, this study compared belted front seat occupants in integrated seats with occupants of closely matched models with conventional seats. This matching approach is used in many social and epidemiological studies such as comparing patients treated in the same hospital, students in the same class, and members of the same household. It has the advantage of equalising confounding factors that are difficult to enumerate, measure, or control in an analysis [19-20]. By matching the case and the comparison vehicle closely, differences in vehicle design that may otherwise affect injury propensity are greatly reduced. For example, the 2001–2008 Ford F-150 Super Cab had SIRS at the front outboard positions. The comparison is the same model years' F-150 Super Crew Cab pickup where the front outboard seats had conventional pillar-anchored lap-shoulder belts. The Chevrolet pickups present a different scenario. The first generation of the Chevrolet Silverado 1500 pickup (1999–2006) all had SIRS but changed to conventional seats in the next generation (2007–2013). Since matching within the same model years was not possible, a "sandwich" approach was used where vehicles of the same model line from several model years before and several model years after were used as comparisons. This avoided potential biases that may be introduced by comparing with strictly newer or strictly older models. Similar approaches were used to identify closely matching models as comparisons for each model with SIRS. For certain models, only predecessor or successor models were available to serve as comparisons. Closely matched model pairs also broadly even up the characteristics of the driver and driving behaviour; factors that are difficult to measure and adjust for in an analysis. Table A1 in Appendix A show the list of matching model pairs used in this analysis. It should be noted that some SIRS equipped vehicles were excluded due to their lack of data, e.g., Saab 9-7X, Ferrari 612 (the lack of data is because of low volume for both models). Incomplete vehicles, e.g., chassis cabs or other automobile derivatives, e.g., campers, tow trucks were also excluded. Only front outboard seat occupants were in this analysis; all other occupants were excluded. Appendix A provides additional information on the coding and variables selected.

Statistical Analysis

The data consists of driver and right front passenger records from each Seat Integrated Restraint Systems (SIRS) model and its comparisons. Exposure to the SIRS is regarded as the "treatment". The crash event was regarded as the "experiment" and the outcome of interest was injuries sustained from the crash. Serious-to-fatally injured (MAIS 3+F) occupants were identified using the Maximum Abbreviated Injury Scale (MAIS) level three or higher or with fatality. The first hypothesis tested is whether SIRS availability increases restraint use. For this hypothesis, use or non-use of the seatbelt is the binary outcome. This hypothesis examined if occupants in SIRS were more likely to wear a seatbelt than similar models with conventional seats and pillar-anchored seat belts (non-SIRS). The second hypothesis examined whether the risk for serious injury (MAIS 3+F) in SIRS and in non-SIRS is comparable.

In addition to front-outboard seat types (SIRS/non-SIRS), there were other factors, unrelated to the seat design, that could influence the likelihood of injury. To control for these other factors, the following covariates were included in the logistic model[1]:

- Data Source (CDS or CISS)
- Age and sex of occupant

[1] Special treatments of the underlying variables and other coding details is provided in Appendix A.

- Seat position of occupant (driver, right front)
- Vehicle type: passenger cars, SUVs, pickups
- Crash type (front, rear)
- Severity of the impact (delta-V range)
- Deployment of frontal airbags

Please see Appendix A for additional information.

The SAS statistical software (Release 9.4) was used to process the CDS and CISS data, as well as carrying out statistical modelling of the data. SAS's SURVEYLOGISTIC procedure is designed for logistic regression with survey data. The odds ratio (OR) associated with seat type estimated from the logistic model represents an estimate of the ratio of the odds of injury between integrated and conventional seats occupants. The null hypothesis is equivalent to testing OR=1; a non-significant odds ratio (p>0.05) is equivalent to finding that two types of seats have comparable and statistically indistinguishable injury risk.

Matched-pair data is a type of stratified data, which is often analysed using conditional logistic regressions. However, the stratification provision in SURVEYLOGISTIC is reserved for characterising the survey design and cannot be used to conduct stratified or conditional logistic modelling with survey data. To account for the survey design, the SURVEYLOGITIC was invoked in two ways. First, instead of a stratified analysis, a non-stratified analysis was conducted comparing the integrated and conventional seat models as two vehicle groups. The odds ratio associated with the seat type estimated from such a model represented an estimate of the average difference between integrated and conventional seats across these models after adjusting for other covariates. Second, the SURVEYLOGISTIC was invoked repeatedly for each model pair, resulting in a set of odds ratios, each having been estimated after adjusting for other confounding factors as in the other logistic model, as well as correctly accounting for the design of the survey. An overall odds ratio for the seat type effect was estimated from this set of individual model odds ratios using meta-analysis procedures, which were developed for combining results from independent studies, for these calculations [3]. The average effect was a weighted average of the odds ratio from each model pair in the study. The weight used was the inverse of the variance of the log-odds. For this study, the meta-analysis calculations did not assume the effect associated with the integrated seat as having a single common true value (i.e., fixed effect), but a range of values, or more generally, a distribution of effects sizes, depending on factors such as the vehicle type and size and shape of the vehicle. This approach (i.e., random effects) is more rational, as one common integrated-seat effect being applicable across all models from full-size trucks to sporty convertibles is unrealistic. The effect of the integrated seat computed from the two SURVEYLOGISTIC approaches would be presented and discussed.

III. RESULTS

The number of front outboard occupants (FOB) with integrated seats (SIRS) and conventional seats (non-SIRS) was determined using the vehicles identified in Table A1. There were an estimated 6,523,290 (13,563 unwgt) belted and unbelted front-outboard occupants, 87.1% of which were belted. The belt use was determined as the number of belted occupants divided by the sum of belted and unbelted occupants; it did not control or adjust for any other factors. Of the belted FOB, 2,450,311 (5,093 unwgt) were in SIRS seats and 3,234,205 (5,829 unwgt) in non-SIRS. Please see Table B1 in Appendix B for additional information. Among the belted FOB, 25.6% were in passenger cars, 40.6% were in pickup trucks, and 33.7% were in SUVs.

Table 1 summarises the demographic profile of belted FOB. Age and sex had only negligible fraction with unknowns (1–2%) values, but race was not as complete with more than 30% unreported[2]. The results in Table 1 were calculated with known values only. Occupants 13 or older were included in the analysis to avoid analysing occupants in child seats where belt use and injury may involve other factors unrelated to the SIRS. For belted FOB in pickup trucks with SIRS, 49.6% were younger than 40, 79.1% were males, and 91.6% were white. In comparison, 60.0% of belted FOB in non-SIRS in pickup trucks were younger than 40, 81.5% were males, and 85.4% were white. Almost 44% of passenger car belted FOB were elderly when seated in SIRS, compared with <12% in pickup trucks and SUVs. About 80% of pickup truck occupants were males, compared with only 50% in passenger cars and 54–55% in SUVs. About 82–84% were drivers and 16–18% were right front passengers, with only small differences between vehicle types.

Table 1

Demographic Profile of Integrated and Conventional Belted FOB Occupants

		Cars		Pickups		SUVs		Total	
Factors		SIRS	Non-SIRS	SIRS	Non-SIRS	SIRS	Non-SIRS	SIRS	Non-SIRS
Age	13–39	34.5	45.5	49.6	60.0	57.0	65.2	49.5	57.1
	40–64	22.0	33.5	39.4	32.8	33,6	28.7	34.2	31.7
	65+	43.5	21.0	11.0	7.1	9.4	6.2	16.3	11.2
Sex	Male	50.2	50.8	79.1	81.5	53.7	55.9	64.7	63.7
	Female	49.8	49.2	20.9	18.5	46.3	44.1	35.3	36.3
Race	White	84.2	76.8	90.9	85.5	76.1	76.6	84.2	80.1
	Black	12.9	18.4	6.3	10.1	20.9	10.9	12.9	13.0
	Other	2.9	4.8	2.8	4.4	3.1	12.5	2.9	6.9
Pos	Driver	83.4	82.7	86.1	82.0	81.1	80.9	83.8	81.9
	RFP	16.6	17.3	13.9	18.0	18.9	19.1	16.2	18.1

RFP: Right-front passenger.

Hypothesis 1 – Seatbelt Use Comparison

Hypothesis 1 evaluates whether seatbelt use increased with Seat Integrated Restraint Systems (SIRS) in comparison with vehicles with conventional seat belts (non-SIRS). Table 1 shows seatbelt use in the SIRS and in non-SIRS. It was 86.5% (95% CI: 84.1%–88.9%) in SIRS and 87.7% (95% CI: 85.5%–89.9%) in non-SIRS overall. The resulting relative use rate was 0.99 (95% CI: 0.96-1.02, p=0.397), which was not significant. These results suggest that vehicles with SIRS neither encouraged nor discouraged the occupants to use seatbelts compared with conventional seats (non-SIRS) with typical pillar anchored seatbelts.

[2] Before 2009, the CDS only collected race of the driver, race of other occupants are all unknown.

Table 2
Belt Use for Front Outboard Occupants in SIRS and in Conventional Seats (non-SIRS)

	SIRS	Non-SIRS		
	Use% & 95% CI	Use% & 95% CI	RR & 95% CI	p-value
Overall	86.5 (84.1–88.9)	87.7 (85.5–89.9)	0.99 (0.96–1.02)	0.397
Passenger Cars	89.3 (85.4–93.2)	88.8 (83.9–93.6)	1.01 (0.95–1.06)	0.809
LTVs*	85.9 (83.0–88.7)	87.6 (84.1–90.2)	0.99 (0.95–1.02)	0.387
Pickups	85.3 (82.1–88.6)	85.7 (81.4–90.1)	1.00 (0.94–1.06)	0.873
SUVs	86.5 (82.0–91.1)	88.8 (85.3–92.3)	0.97 (0.93–1.02)	0.225

*LTV: Pickups and SUVs combined

To further examine the hypothesis more closely and adjusting for other confounding factor, a logistic regression was conducted with seatbelt use as the outcome. Injury status, which is an outcome of the collision, logically cannot affect the pre-collision seatbelt use and was not included in the model. Consistent with the un-adjusted comparison, there was no difference in seatbelt use between occupants in vehicles with SIRS and conventional seats (non-SIRS), with belt use ratio of 0.99 (95%CI: 0.96–1.02, p=0.397). The covariates that showed a significant association with seatbelt use included: age (p=<0.001), sex (p=0.0001), impact severity (p=<0.001), and single or multiple vehicle accidents (p=0.002). Vehicle type and crash type were not associated with seatbelt use (p=0.9946 & 0.9783). Being a driver or a right front occupant also had no effect on seatbelt use (p=0.5114). Similarly, whether the airbag was deployed also showed no association with seatbelt use (p=0.8222).

Hypothesis 2 – Injury Risk for Belted Occupant

Hypothesis 2 evaluates whether belted occupants in SIRS have lower risk of serious injury than occupants in conventional seatbelts (non-SIRS). Please see Table B2 for a summary of the injury analysis for belted front outboard seat (FOB) occupants in SIRS vehicles and those with serious-to-fatal injury (MAIS 3+F). The injury risk (in percent) and the corresponding 95% confidence interval, as well as the relative risk (RR) between SIRS and conventional seat (non-SIRS) occupants were calculated. The sample size is also listed as the unweighted number of occupants involved and the number with serious injury (MAIS 3+F). It should be noted that the calculations shown in the analysis incorporated sampling weights and other sample design factors. The data was analysed by vehicle and crash type. The injury risks presented were crude, or unadjusted, values and the difference may be the results of differences in occupant characteristics or in the crash nature or severity. Subsequent statistical modelling would attempt to adjust for these confounding factors and to arrive at a more accurate estimate of the difference in injury risk between integrated (SIRS) and conventional seats (non-SIRS).

Figure 1 compares the risks in SIRS and non-SIRS in all, in frontal and in rear crashes. Similarly, Fig. 2 shows the risk by crash type for passenger cars and light truck vehicles, which combined SUV and pickup truck data. Overall, there was no difference in the injury risk between belted occupants in SIRS and conventional seats (p=0.222). The relative risk (RR) was determined as the risk of injury with SIRS divided by the risk with non-SIRS. The RR was greater than 1, indicating higher risk in a SIRS than a conventional seat. The risk in frontal crashes was 3.31%±0.94% in SIRS and 1.18%±0.27% in non-SIRS; the RR was marginally significant (p=0.061), primarily due to differences in front collisions where the SIRS had a significantly higher injury rate compared with conventional seats (3.24% vs. 1.22%, RR=2.65, p=0.002) (Fig. 2). The data for SUV and pickup trucks was combined to increase the sample size. The results are shown in Fig. 2 as LTV (light truck vehicles). Though the injury risks were higher in SIRS than in non-SIRS, the results were not statistically significant; there was no difference in injury risk for belted FOB occupants in LTVs, regardless of area of crash type (all, front and rear). Please see Table B2 for additional information.

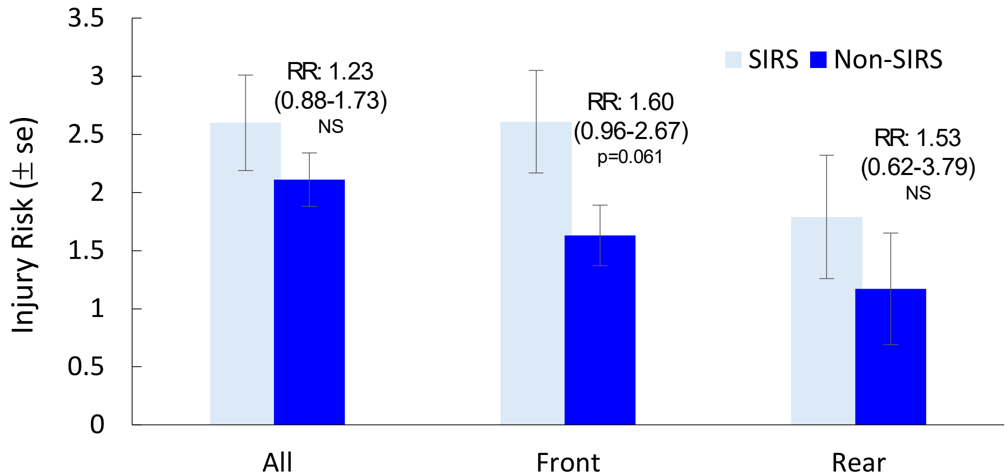

Fig. 1: Risk of serious injury for belted FOB in SIRS and non-SIRS by crash types.

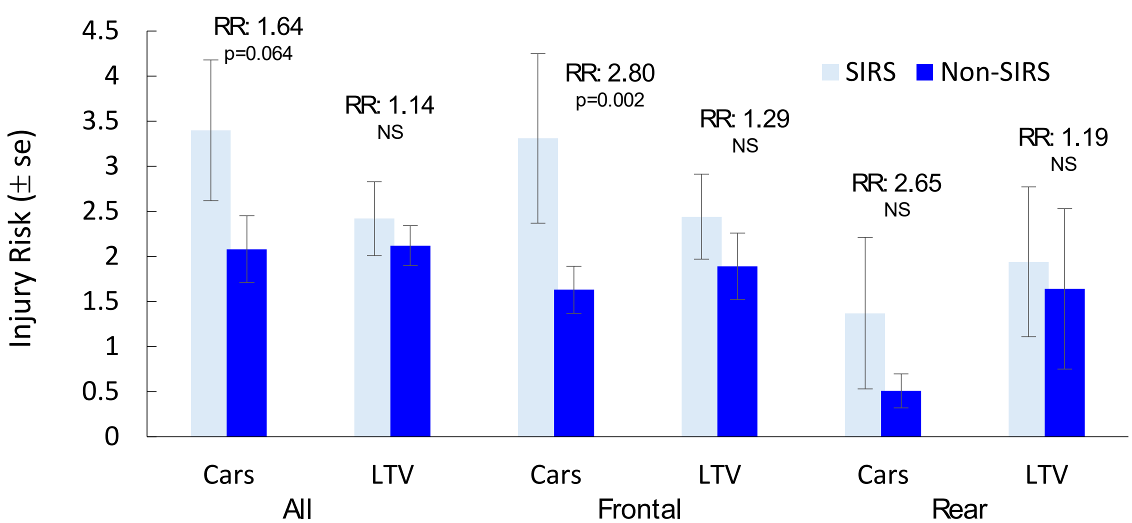

Fig. 2: Risk ± standard error of serious injury for belted FOB in SIRS and non-SIRS by vehicle and crash types.

Logistic Regression with Survey Data

An additional analysis was conducted using SURVEYLOGISTIC to assess association between SIRS and injury, controlling for several other factor that may confound the injury risk results. Table 4 summarises the analysis for each covariate. It shows the overall significance measured by the Type 3 F-statistics value and the specific odds ratios representing the comparison between each level of the covariate with its reference. There was no injury risk difference between belted occupants in SIRS and conventional seats (p=0.179). The covariates that showed a significant association included: age (p<0.01), sex (p=0.038), crash severity (p<0.001), deployment of airbag (p<0.001). Vehicle type and seat position were not significant. Single or multiple vehicle accidents had no effect on injury (p=0.539). The average injury risk for FOB occupants in integrated seats was 1.60% (95% CI: 0.36-1.01) and the corresponding risk for conventional seat occupant was 1.25% (95%: 0.26-0.82). The resulting injury risk odds ratio was 1.26 (95% CI: 0.89-1.79, p=0.179), which was not significant.

Table 3

Parameter Estimates from Survey-Based Logistic Regression

			Type 3 Effect			OR Comparisons		
Effect	Level	Ref.	Df	F Value	Pr> F	OR	95% CI	p-values
Seat			1	1.87	0.178	1.26	0.89–1.79	0.179
Age			2	7.27	0.0023			
	65+	13–39				2.37	1.42–3.96	0.002
	40–64	13–39				1.72	1.16–2.54	0.008
Sex	Male	Female	1	4.65	0.038	0.73	0.54–0.98	0.038
Vehicle Type			2	0.09	0.9147			
	SUV	Cars				1.03	0.76–1.40	0.835
	Pickup	Cars				0.94	0.59–1.52	0.811
Crash Type			1	6.28	0.008			
	Rear	Front				1.35	0.79–2.31	0.270
Crash Severity (km/h)			3	32.75	<0.001			
	25-<55	00-<25				3.14	2.16–4.58	<0.001
	55+	00-<25				19.8	10.7–36.59	<0.001
	Unknown	00-<25				1.59	1.05–2.42	0.029
Airbag	Not Deploy	Deploy	1	26,28	<0.001	0.32	0.21–0.51	<0.001
Location	Right Front	Driver	1	1.95	0.1715	1.27	0.90–1.78	0.172
Vehicles	Single	Multiple	1	0.38	0.5393	1.15	0.73–1.81	0.539

IV. DISCUSSION

SIRS were initially developed to facilitate belt use in various vehicle body designs. The use of SIRS seats for the first-row occupants is negligible today due to several reasons, including customer comfort and convenience, weight, packaging issues and incompatibility of advanced belt technologies.

Nonetheless, SIRS are currently being considered for future use in autonomous driving for unconventional seating arrangements. It is thus important to understand their field performance based on real world accident data. There is limited information on this topic in the literature. Padmanaban et al. [3][17] investigated police-reported rear crashes to assess the effect of seat strength and stiffness on the risk of injury. The authors found no statistically significant relationship between seatback stiffness and serious-to-fatal injury risks for drivers or rear occupants in rear-impacts. Their analysis included conventional (non-SIRS) and SIRS. They reported that SIRS were not a statistically significant factor in influencing serious-to-fatal injuries to belted drivers in rear crashes. SIRS are generally stronger and stiffer than non-SIRS in order to support shoulder belt loads in frontal crashes [22]. In 2009, Padmanaban et al. [21] used compared ejection and injury risks of belted drivers in SIRS and non-SIRS involved in rollover crashes. Conventional seats (non-SIRS) and SIRS were identified in similar make and models. Using a similar methodology, the current analysis examined the relative performance of SIRS and non-SIRS using investigated tow-away field accidents. Belted front outboard occupants (FOB) in integrated seats (SIRS) were compared to occupants in conventional seats of closely similar models. This matched comparison allows a better isolation of SIRS safety performance un-confounded by other vehicle features. The data was analysed for 13 years and older FOB to exclude children in child restraints.

The data was limited to passenger cars, SUVs and pickup trucks since there are no SIRS available in vans in the front-outboard seat location. The distribution of exposed FOB in SIRS and conventional seats (non-SIRS) was assessed by vehicle type and belt use (Appendix B1). For belted FOB in SIRS, about 26% were in passenger cars, 41% in pickups and 34% in SUVs. Two hypotheses were evaluated in this study: 1. SIRS encouraged belt use, and 2. Injury risks were different in SIRS and non-SIRS. The results indicated seatbelt use was similar in SIRS and non-SIRS, negating the first hypothesis. Overall, belt use was 86.5% (95% CI: 84.1%-88.9%) in SIRS and 87.7% (95%CI: 85.5%-89.9%) in non-SIRS. The risk of serious injury was greater in SIRS than non-SIRS, irrespective of vehicle and crash types. However, the results were not statistically significant overall. It was only statistically significant in frontal crashes. In a frontal impact, front seat occupants move forward and load the restraint system. The restraint couples the occupant to the vehicle and applies restraining force to accelerate the occupant to the vehicle's speed while limiting their excursion. In a SIRS, the upper anchor is attached to the seatback. The seatback rotates forward with occupant restraint loading depending on the occupant size and crash severity. It can thus be challenging to optimise a restraint system for various size occupants when the upper anchor is not fixed. In rear crashes, the injury risk was higher with SIRS than non-SIRS, however no statistical difference was observed, consistent with prior studies [21]. There are known downsides of SIRS use in rear impacts including higher risks for older and more frail occupants and/or occupants with spinal degeneration [23]. Most rear crashes occur at lower speeds. An analysis of rear sled tests conducted by the Insurance Institute Highway Safety with SIRS and conventional seats showed significantly higher risks with the SIRS seat in 16 km/h rear crashes [24]. Furthermore, the upper anchor mounting creates stiff structure in the occupant compartment which can be contacted in crashes and can become a source of injury. For example, Viano et al. conducted 48 km/h with a 95th percentile anthropometric test device (ATD) seated in a SIRS [13]. When the ATD was leaned forward and outboard, the back of head struck the shoulder belt anchor mounting structure, also called stanchion. The impact resulted in high head acceleration and neck extension. Furthermore, Kang et al. [25] conduced 56 km/h rear sled tests with Post Mortem Human Subjects in a reinforced SIRS seat and observed scapula fractures coinciding with the location of the shoulder belt anchor mounting structure on top outboard side of the seatback.

In this study, the field performance of SIRS was assessed by comparing injury risk of vehicles with and without SIRS. The vehicles were matched using the same make and model with a prior and older generation. This match-pair method allowed to account for design changes.

V. CONCLUSION

SIRS are potentially considered for new seating configurations made possible with autonomous driving technologies. New configurations include rear-facing seats. Since most crashes are frontal, understanding the field performance in front and in rear crashes is important. The results from this study indicate that SIRS do not provide a safety benefit; belt use was similar in SIRS and non-SIRS, and injury risks were higher in SIRS than non-SIRS in frontal crashes.

VI. ACKNOWLEDGEMENT

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Appendix A: Coding definitions

NASS-CDS - NHTSA's Crashworthiness Data System (CDS), started in 1988, is a stratified sample of collisions in which one or more passenger vehicles were towed. In 2015, the last year of the program, CDS sampled 2,634 crashes involving 4,815 vehicles. The CDS program was re-designed and replaced by the Crash Investigation Sampling System (CISS) in 2016. In 2017, the first full year of CISS, 2,035 crashes involving 3,748 vehicles were sampled.

NASS-CISS - The sampling universe of the CISS is very similar to that of the CDS, requiring at least one crash-involved vehicle to be towed[3]. Information is collected from all crash-involved vehicles, regardless of towing status. However, occupant and injury details are compiled only from those in the towed vehicles. In addition to the basic information from the police report, NHTSA field investigators would attempt to locate the crashed vehicles for inspection and detailed measurements of deformation and intrusion. Investigators also would interview occupants and obtain medical records of the injured to assemble a comprehensive record for the case.

This section provides some technical details and documentation about the codes used in the analysis and how certain variables from the CDS and CISS are treated. It also details certain exclusions used in this analysis and how they are implemented.

Data Source – this indicator variable signals if a particular record originated from the CDS or the CISS. Although the CDS and the CISS have the same goal, their sampling designs are different, and NHTSA recommend treating them as two independent survey systems. In SURVEYLOGISTIC, this factor is treated as another level of stratification.

Light Passenger Vehicle – light passenger vehicle is typically defined by NHTSA as those having body type code 01 to 49.

Crash Type – Impact location was used in CDS and CISS to identify the type of crash (front/rear). If the impact location was unknown, the direction of force was used.
For example,

- STEP1: Frontal impacts were first identified using GAD1='F'.
- STEP2: If GAD1 was missing or unknown, then frontal impacts were identified using DOF1 in (11,12,01,21,31,32,41,51,52,61,71,72,81,91,92).
- STEP3: If impact location and impact direction were missing or unknown, then the "crashtype" variable was used.

Rollovers were excluded.

[3] The CDS requires the vehicle to be towed due to damage. The CISS is less restrictive, and the vehicle can be towed for any reason. Starting in 2019, the CISS towing variable distinguish towed due to damage and towed due to other reasons. The CISS data showed that about 1-2% of the towed vehicles were towed for non-damage related reasons.

Crash Severity– severity of the collision is directly related to the propensity of injury. NHTSA field investigators had calculated the “delta-V” for some crash-involved vehicles, but not every type of collision or every crash-involved vehicle had this measured calculated. The CDS and CISS also provide a delta-v range and qualitative delta-v categories for those cases where precise delta-v calculation was not feasible. We combined both the calculated and the estimated delta-v into a 3-level crash severity categorical factor: <25 km/hr, 25-54 km/hr, 55 and above km/hr.

Single/multi-vehicle – an indicator variable was established to signal if the crash was a single vehicle event or if other vehicles were involved.

Seat Position – The CDS and CISS have detailed seating position codes. For this analysis, only occupants in seating position 11 (driver) or 13 (right front) are included.

Seats – The CDS and the CISS have a variable[4] since 2003 that denotes the presence of a SIRS when the crash-involved vehicle was inspected by the NHTSA investigators. This variable was used to generate a preliminary list of models with integrated restraint systems for this analysis. Several earlier studies on seatback stiffness and integrated seat performance in rollovers by Padmanaban and Burnett [21] also provided helpful information on models with integrated restraints. Other automotive literature (e.g., sales brochures) and internet sites with extensive collection of vehicle specifications and pictures[5] were also used to verify presence of these restraint systems.

Table A1

Matched Model Pairs in Integrated Seat Comparison

	Integrated Seats (SIRS)		Conventional Seats (Non-SIRS)	
Passenger Cars				
BMW	3 Series Convertible	1997–2013	3 Series Sedan, Coupe	1997–2013
BMW	6 Series Convertible	2004–2010	6 Series Coupe	2004–2010
Buick	Park Avenue	1997–2005	Park Avenue	1991–1996
			Lucerne	2006–2011
Buick	LeSabre	2000–2005	LeSabre	1995–1999
			Lucerne	2006–2011
Cadillac	CTS, CTS-V	2003–2007	CTS, CTS-V	2008–2013
Cadillac	DeVille	2000–2005	DeVille	1994–1999
			DTS	2006–2011
Cadillac	SeVille/STS	1998–2004	SeVille	1992–1997
			STS	2005–2011
Chrysler	Sebring Convertible	1996–2010	Sebring Coupe/Sedan	1996–2010
Mercedes	SL/CL Coupe/Convertible	2000–2011	S Sedan	2000–2011
Oldsmobile	Aurora	2001–2003	Aurora	1995–1999
Pontiac	Bonneville	2000–2005	Bonneville	1992–1999

[4] In CDS, the variable is INTGREST, and in CISS, the variable is INTRESTRAINT. Both are in the occupant data file.
[5] The source of vehicle specifications and pictures checked include such sites as: Car and Driver (www.caranddrive.com), JD Power (www.jdpower.com), and Kelley (www.kbb.com).

Pickup Trucks[6]

Chevrolet	Avalanche	2002–2006	Avalanche	2007–2013
Chevrolet	C/K Silverado 1500	1999–2006	Silverado 1500	2007–2010
			C/K 1500	1995–1999
	C/K Silverado 2500	1999–2006	Silverado 2500	2007–2010
			C/K 2500	1995–1999
	C/K Silverado 3500	2001–2006	Silverado 3500	2007–2010
			C/K 3500	1995–1999
Dodge	Ram Club Cab	1995–2001	Ram Regular Cab	1995–2001
	Ram Quad Cab	1998–2001	Ram Regular Cab	1998–2001
Ford	F-Series Super Cab	2001–2008	F-Series Super Crew	2001–2008
	F-Series Regular Cab	2005–2008	F-Series Regular Cab	2001–2004
GMC	C/K Sierra 1500	1999–2006	Sierra 1500	2007–2010
			R/V Pickup 1500	1995–1999
	C/K Sierra 2500	1999–2006	Sierra 2500	2007–2010
			R/V Pickup 1500	1995–1999
	C/K Sierra 3500	2001–2006	Sierra 3500	2007–2010
			R/V Pickup 1500	1995–1999

SUVs

Buick	Rainier	2004–2007	Olds Bravada	1996–2004
Cadillac	Escalade	2002–2006	Escalade	2007–2014
			Escalade	1999–2000
Cadillac	SRX	2004–2009	SRX	2010–2016
Chevrolet	Tahoe	2000–2006	Tahoe	2007–2014
			Tahoe	1992–1999
Chevrolet	Suburban	2000–2006	Suburban	2007–2014
			Suburban	1992–1999
Chevrolet	Trailblazer	2002–2009	Traverse	2009–2017
			Blazer (S10)	1999–2001
GMC	Yukon	2000–2006	Yukon	2007–2014
			Yukon	1992–1999
GMC	Yukon Denali	2001–2006	Yukon Denali	2007–2012
			Yukon Denali	1999–2000
GMC	Envoy	2002–2009	Envoy	1998–2000
Honda	Elements	2006–2011	Elements	2003–2005
Isuzu	Ascender	2003–2008	Axiom	2002–2004
Oldsmobile	Bravada	2002–2004	Bravada	1998–2001

Although a few vehicles had integrated seats in the 1980s, increased application of this seat design began in the mid-1990s and integrated seats were adopted in many cars and truck models from 2000 to 2009, especially from domestic manufacturers. Its use declined after 2010 and was used only in a few convertibles in later model years. For this analysis, vehicles with SIRS were targeted and comparable models in a similar model year range were selected as comparisons.

[6] The medium (¾ ton) and heavy duty (1 ton) pickup trucks were grouped with the light duty (½ ton) models.

Restraint Use – The CDS and CISS have very detailed information from multiple variables that related to the availability and use of restraint. For this study, belted occupants were identified using "MANUSE/BELTUSE" in (4,12,13,1415,18). If unknown, the police reported the variable "PARUSE/PARBELTUSE" in (2,3,4,5,7,8) was used. Unbelted occupants were identified using "MANUSE/BELTUSE" in (0,1). If unknown, the police reported the variable "PARUSE/PARBELTUSE" in (0,1,10) was used.

Airbag deployment: Vehicles are equipped with different airbag. In this study, an airbag deployment included any airbag deployment and was identified using "BAGDEPLOY" in (1,2,3,4). If unknown, "BAGCDC" in (1,2,3,6) was used. If both variables were unknown, "PARAIRBAG" in (2) was used.

Occupant Age – NHTSA's recommendation is for all children 12 years or younger to be in car seats or booster seats. The occupants included in this analysis were restricted to those who sat in a regular seat, with or without restraint. Age 13 and above was chosen for this purpose. Age is grouped into 13–24, 25–44, 45–64, 65 and above. Age of occupant is well coded in the CDS/CISS with <2% with unknown age.

Occupant Sex – Sex of occupant is well coded in both CDS and CISS, with only 1% unknown values.

Occupant Height/Weight – Occupant's height and weight are captured in both CDS and CISS. Overall, however, both factors showed having over 30% of records with missing value, which would cause substantial loss of data. If certain occupants' characteristics (e.g., injury status) are tied to height/weight being missing, unwanted bias could be introduced. For these reasons, these two factors were not included in the regression models.

Appendix B: Data

Table B1: Front-outboard occupants (FOB) by seat, vehicle type.

	Belted FOB			Unbelted FOB			Restraint use
	unwgt	wgt	%	unwgt	wgt	%	%
Seats				**All Crashes**			
				Total			
SIRS	5,093	2,450,311	100%	1,282	383,397	100.0%	86.5%
Non-SIRS	5,829	3,234,205	100%	1,359	455,377	100.0%	87.7%
Total	10,922	5,684,516	100%	2,641	838,774	100.0%	87.1%
				Pass Car			
SIRS	1,011	443,099	18.1%	221	52,917	13.8%	89.3%
Non-SIRS	2,087	1,014,725	31.4%	382	128,563	28.2%	88.8%
Total	3,098	1,457,824	25.6%	603	181,480	21.6%	88.9%
				Pickup			
SIRS	2,218	1,126,464	46.0%	631	193,418	50.4%	85.3%
Non-SIRS	1,874	1,181,835	36.5%	583	196,410	43.1%	85.7%
Total	4,092	2,308,298	40.6%	1,214	389,829	46.5%	85.6%
				SUV			
SIRS	1,864	880,749	35.9%	430	137,062	30.1%	86.5%
Non-SIRS	1,868	1,037,645	32.1%	394	130,404	34.0%	88.8%
Total	3,732	1,918,394	33.7%	824	267,465	31.9%	87.8%
				Frontal Crashes			
				Total			
SIRS	2,781	1,369,069	100%	648	238,912	100.0%	85.1%
Non-SIRS	3,166	1,689,770	100%	721	261,155	100.0%	86.6%
Total	5,947	3,058,839	100%	1,369	500,067	100.0%	85.9%
				Pass Car			
SIRS	554	271,581	19.8%	123	30,165	12.6%	90.0%
Non-SIRS	1,150	621,674	19.2%	229	97,249	21.4%	86.5%
Total	1,704	893,255	15.7%	352	127,414	15.2%	87.5%
				Pickup			
SIRS	1,258	617,399	25.2%	333	121,266	50.8%	83.6%
Non-SIRS	1,033	589,158	18.2%	304	97,797	21.5%	85.8%
Total	2,291	1,206,557	21.2%	637	389,829	46.5%	75.6%
				SUV			
SIRS	969	480,089	19.6%	192	87,480	19.2%	84.6%
Non-SIRS	983	478,939	14.8%	188	66,108	27.7%	87.9%
Total	1,952	959,028	16.9%	380	153,588	18.3%	86.2%
				Rear Crashes			
				Total			
SIRS	287	119,355	100.0%	20	10,450	100.0%	91.9%
Non-SIRS	347	156,829	100.0%	18	26,998	100.0%	85.3%
Total	634	276,184	100.0%	38	37,448	100.0%	88.1%
				Pass Car			
SIRS	88	33,057	27.7%	6	587	5.6%	98.3%
Non-SIRS	149	65,594	41.8%	6	3,239	12.0%	95.3%
Total	237	98,651	35.7%	12	3,826	10.2%	96.3%
				Light Truck (PU&SUV)			
SIRS	199	86,299	72.3%	14	9,863	94.4%	89.7%
Non-SIRS	198	91,234	58.2%	12	23,759	88.0%	79.3%
Total	397	177,533	64.3%	26	33,622	89.8%	84.1%

Table B2: Belted front-outboard occupants (FOB) injury risk by crash, seat and vehicle type.

	SIRS				Non-SIRS					
	Occ.	MAIS3+F	Risk	95% CI	Occ.	MAIS3+F	Risk	95% CI	RR & 95% CI	p-value
	unwgt			wgt	unwgt			wgt	wgt	
All vehicles										
All	5,093	581	2.60 ±0.41	1.84-3.56	5829	739	2.11±0.23	1.84-3.56	1.23 (0.88-1.73)	0.222
Front	2,781	271	2.61 ±0.44	1.78-3.68	3,166	316	1.63±0.26	1.14-2.26	1.60 (0.96-2.67)	0.061
Rear	287	18	1.79 ±0.53	0.59-4.08	347	20	1.17±0.48	0.32-2.95	1.53 (0.62- 3.79)	0.366
Cars										
All	1,011	163	3.40±0.78	1.99-5.39	2,087	273	2.08±0.37	1.39-2.99	1.64 (0.95-2.83)	0.065
Front	554	83	3.31±0.94	1.68- 5.80	1,150	118	1.18±0.27	0.64- 1.99	2.80 (1.31-6.00)	0.002
Rear	88	5	1.37±0.84	0.06-6.56	149	9	0.51±0.19	0.005-3.42	2.65 (0.61- 11.5)	0.202
Light Trucks (PU & SUV)										
All	4082	418	2.42±0.41	1.66-3.41	3742	466	2.12±0.22	1.68-2.64	1.14 (0.77- 1.68)	0.497
Front	2,227	188	2.44±0.47	1.57-3.60	2,016	198	1.89±0.37	1.22-2.81	1.29 (0.66-2.50)	0.445
Rear	199	13	1.94±0.83	0.52-4.97	198	11	1.64±0.89	0.36-4.58	1.19 (0.30- 4.69)	0.801
Pickups (PU)										
All	2,218	242	2.55±0.56	1.53-3.96	1,874	228	1.98±0.26	1.40-2.72	1.28 (0.71-2.32)	0.398
Front	1,258	115	2.55±0.64	1.42-4.20	1,033	93	1.70±0.45	0.91-2.88	1.50 (0.60-3.75)	0.375
Rear	100	5	0.98±0.68	0.02-5.42	81	6	2.48±2.09	0.14-10.9	0.40 (0.05-3.48)	0.352
SUVs										
All	1,864	176	2.26±0.44	1.46-3.35	1,868	238	2.28±0.38	1.58-3.17	0.99 (0.62-1.58)	0.978
Front	969	73	2.29±0.71	1.08-4.25	983	105	2.14±0.54	1.18-3.55	1.08 (0.47-2.48)	0.862
Rear	99	8	3.12±1.82	0.59-9.24	117	5	1.24±0.80	0.13-5.77	2.52 (0.49- 12.95)	0.298