Accident Analysis and Prevention 190 (2023) 107180

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

The effect of seatbelt pre-tensioners and load limiters in the reduction of MAIS 2+, MAIS 3+, and fatal injuries in real-world frontal crashes

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A R T I C L E I N F O

Keywords:
Seat belts
Pre-tensioners
Load limiters
Frontal impacts

A B S T R A C T

Contemporary research has pointed out that while newer cars are contributing to the decrease of AIS2+ and AIS3+ injuries in several body regions, this effect is not shown for thoracic injuries like rib or sternal fractures. The objective of this study is to assess the effectiveness of advanced seat belt systems incorporating pre-tensioners and load limiters in the prevention of fatal, AIS2+ and AIS3+ injuries overall and then focus only on the head-face-neck and thoracic areas. Data from the NASS CDS database between 2000 and 2015 was augmented with specific vehicle information taken from NHTSA's NCAP tests to identify the characteristics of the seat belt of each vehicle involved in a collision. Multivariate logistic regressions were developed to assess the likelihood of injuries for belted front seat occupants in frontal impacts. The presence of pre-tensioners and load limiters with a low load limiter (<4.5 kN) was significantly associated with a decreased risk of fatal and AIS3+ in the whole body (OR = 0.31 ($p < 0.05$) and OR = 0.70 ($p < 0.1$)), while high load limiters were significant in the prevention of fatal injuries (OR = 0.42). These effects should be considered always in combination with the delta-v of the collision, as the interaction term between delta-v and advanced seat belt features was significant. In the crashes considered, the model predicted a higher risk of injury for women compared to men, controlling for other occupant and crash factors. Impacts with a slightly oblique component increased the risk of injury compared to pure frontal impacts. After controlling for the presence of pre-tensioners and load limiters, the vehicle model year variable was found to be insignificant in any of the regression models. This study shows that the real-world effectiveness of advanced seat belts still requires further analysis. Other effects like age or impact direction might be more influential in the injury outcome than these seat belt features.

1. Introduction

According to the last available data from the Fatality Analysis Reporting System (FARS), there were 38,824 motor vehicle fatalities in the United States in 2020, which represents a 6.8% increase from 2019 (National Center for Statistics and Analysis, 2022). As for non-fatal injuries, the National Highway Traffic Safety Administration (NHTSA) estimated that around 4.5 million people were injured in motor vehicle crashes in the United States in 2019 (Blincoe et al., 2023). Of these injuries, 806,000 involved severe injuries (AIS3+), according to the Abbreviated Injury Scale (AAAM, 2016)).

A recent analysis of the National Automotive Sampling System Crashworthiness Data System (NASS CDS) showed that newer model-year vehicles significantly reduced the risk of AIS 3+ and AIS 2+ injuries in the lower extremities and in the head but did not find similar effects on the risk of AIS 3+ rib fracture or sternum injury (Forman et al., 2019). The lack of effect of newer vehicles on preventing thoracic injuries is relevant as contemporary restraint systems incorporate advanced features such as multistage airbags, load limiters, and pre-tensioners of varying magnitudes and locations. On the contrary, several other experimental studies using Post Mortem Human Subjects (PMHS) and Anthropomorphic Test Devices (ATD), and also studies using computational human body models (HBM) have suggested that seat belt systems incorporating pre-tensioners and load-limiting features were effective in the prevention of thoracic injuries (Kent et al. 2001; Kent et al., 2007; Forman et al. 2008, 2009; Michaelson et al. 2008).

Previous research has suggested that while experimental studies, whether involving physical or computational testing, may be pertinent for designing and evaluating the nominal impact of more advanced restraint systems, the true effectiveness of these systems can only be estimated when they are assessed using real-world injury data (Segui-Gomez et al., 2009). Using data from FARS, NHTSA estimated that a

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https://doi.org/10.1016/j.aap.2023.107180
Received 8 March 2023; Received in revised form 11 May 2023; Accepted 17 June 2023
Available online 23 June 2023

belted driver or front seat passenger had, on average, an estimated 12.8% lower fatality risk if the seat belt was equipped with a pre-tensioner and a load limiter than if it was not equipped with either. However, the large 95% confidence interval (2.6 % − 23.0 %) suggests that the estimation needs to be refined, perhaps by increasing the size of the analyzed sample (Kahane, 2015).

A non-negligible difficulty for these large epidemiological studies is the challenge of controlling for all the independent variables that might have had an effect on the analyzed outcome. In the specific case of thoracic injuries, such real-world assessment would require that the crash database to be used includes whether the vehicles were equipped with pre-tensioners and load limiters. Moreover, it would also need to include the values at which these systems act on the passengers, as these values differ between different vehicle models. NASS CDS has been an essential source of data for this epidemiological evaluation, given the detailed information that is collected in the system. However, the aforementioned characteristics of advanced seat belts are not included in this database, making it difficult to assess their effect using real-world data.

Thus, the goal of this study is to assess the effect of pre-tensioned and load-limited seat belts in preventing AIS2+ and AIS3+ real-world injuries. To that end, the information included in the NASS CDS database has been augmented with vehicle-specific information that includes the presence of pre-tensioners and load limiters in the seat belt system.

2. Methods

Data were compiled from the NASS CDS for the years 2000–2015. NASS CDS data are selected based on a national-level sampling to represent the frequency of crashes occurring within each of the states of the United States. NASS CDS includes police-reported crashes in which at least one involved vehicle is towed away due to damage, and therefore it is skewed towards collecting more severe crashes. Then, national representativity is achieved by assigning weight factors to each of the approximately 5,000 crashes collected yearly. For each of the collected cases, the database includes information about the vehicle/s involved in the crash (including the vehicle identification number (VIN) that can be used to obtain the maker ID, the model ID, the body type of the vehicle, and the year of manufacturing), a crash reconstruction, the contributing factors from the scene of the collision as well as detailed injury data from the victims. Regarding injuries, beginning in 2010, these were coded in NASS using both the 1998 and 2008 versions of AIS. For consistency, the analyses included in this manuscript were performed using the AIS 1998 codes.

As for the detailed information regarding the characteristics of seat belts, the information included in NHTSA's New Car Assessment Program (NCAP) between 1990 and 2015 was used. The results from the laboratory crash tests performed within the NCAP program are accessible online and were retrieved to characterize whether a tested vehicle had an advanced restraint system. The methodology followed to obtain this information from the performed crash tests is explained in detail in Valdano et al. (2023). In summary, each of the data traces showing the force vs. time response of the seat belt during the crash was analyzed using machine learning algorithms to obtain whether there was a pre-tensioner device included in the shoulder or lap belt retractors and the load limiting force used in the retractor of the shoulder belt.

It should be noted that the NCAP database also included the VIN of the tested vehicles and that this variable was used to augment the data of NASS CDS with the seat belt characteristics obtained after the analysis of the NCAP data. The VIN decoder provided by NHTSA (https://vpic.nhtsa.dot.gov/decoder/) was used to aggregate more information about the vehicle (vehicle maker, model, body type, and year of manufacturing). These four parameters and the occupant position were used to aggregate the seat belt characteristics into the database. Vehicles that were not present in both databases were excluded from the analysis.

First, the NCAP database was filtered to obtain those vehicles with the same maker ID, vehicle ID, and body type. Second, this list of cases from the NCAP database was sorted by year of manufacturing. Third, the year of manufacturing of the vehicle involved in the crash (NASS CDS database) was used to obtain the seat belt characteristics. In the cases in which the manufacturing year of the vehicle did not match the two datasets, the nearest previous test from NCAP was used. Some cases (6 % of all possible combinations) resulted in more than one vehicle tested with the same identifiers. In this case, it was assumed that the vehicle was equipped with the most advanced restraint system found among the possible options (for example, if only one of the coincident vehicles had a pre-tensioner, it was considered that all of them had it). Lastly, the occupant position (i.e., whether the occupant was the driver or front-seat passenger) was also used to obtain the seat belt characteristics.

2.1. Inclusion criteria

NASS CDS data were retrieved for belted drivers and front-seat passengers who were at least 16 years old at the time of the crash. Vehicles included in the analysis were restricted to those built in or after 1990. Only frontal collisions were considered (defined as those with Principal Direction of Force (PDOF) between 11 and 1o'clock) and excluding rollover. From the cases meeting the inclusion criteria above, several variables were chosen to be used as covariables in the analysis: occupant's sex, height, weight, and age, vehicle position of the occupant (driver/front seat passenger), vehicle wheelbase, vehicle age, model year, longitudinal delta-v, PDoF and whether the frontal airbags had deployed. The severity of head and thoracic injuries was also obtained and classified as a dichotomous variable indicating whether the injury severity was AIS2+ or AIS3+ for each body region.

As for the information regarding the restraint systems, the tests included in the frontal crash NHTSA NCAP database were used to retrieve whether the seat belt system of a specific vehicle incorporated a pre-tensioner (dichotomous variable) and/or load-limiting features. Force limiting (LL) was coded as a categorical variable with three levels: no load limiter, low load-limiter force ($\leq$4.5kN), and high load-limiter force (4.5 kN $<$ LL $\leq$ 7 kN). The threshold to classify the load-limiter force as low and high was calculated using the database's 50th percentile of the load-limiting forces.

It should be noted that the pre-tensioner and load-limiting forces were obtained using the transducers placed at the lap and shoulder belt in a crash test. Therefore, the actual force at the pre-tensioner and load-limiting device may differ from the values used in this study.

2.2. Analyses

Descriptive statistics, univariate and multivariate logistic regression models were developed to estimate the effects of independent risk factors on the likelihood of AIS2+ and AIS3+ injuries in the whole body and also to the head-face-neck (HFN) region and the thorax (THO). In the univariate analysis, those variables that showed a significant level of $p < 0.1$ were candidates to be included in the multivariate models. These variables were listed in the previous subsection. After running the multivariate regressions, the variables included in the models were checked for multicollinearity using the Variance Inflation Factor (VIF). Only those variables that resulted in VIF < 2 were kept in the final models. Models including only variables with VIF < 1.5 were also tried out. After eliminating collinear variables, several models were calculated, and those with the lowest AIC values were kept as the best predictors of the outcome. In total, seven outcomes were evaluated using multivariate logistic regression models: the likelihood of sustaining a fatal injury, and the risk of AIS2+ and AIS3+ injuries for the overall body, the head-face-neck body region, and the thorax.

The analysis of the data was performed with the packages Pandas 1.5.2 and Numpy 1.23.1 for data management, and Statsmodels 0.13.5 for statistical modeling within Python 3.10.9, and with RStudio 2021.09.0.

3. Results

3.1. Descriptive analysis

Table 1 shows the distribution of the covariables considered in the study. Categorical variables are described using the number of cases ("N") where this variable was true and its percentage regarding the whole sample. Continuous variables are described by providing their mean and standard deviation (SD).

A total of 14,848 occupants (12,172 drivers and 2,676 front-seat passengers) were included. The age distribution within the sample was 39.1 ± 18.2 years old (mean ± SD), with 48.3% of the sample being male occupants. The mean age of the vehicles involved was 5.1 years old, although the standard deviation was 3.6 years old.

Among these occupants, a lap belt pre-tensioner was present in 700 cases (4.7 %), and a shoulder belt pre-tensioner was included in 5703 cases (38.4 %). The mean value of the pre-tensioner force was similar regardless of the location of the pre-tensioner (1.8 ± 0.6 kN and 1.6 ± 0.5 kN, at the lap belt and shoulder belt, respectively). Two groups were created to analyze the effect of load limiters on the injury outcomes: a group in which the load limiting value was equal to or smaller than 4.5 kN (LL_low) and a second group in which the load limiting value was greater than 4.5 kN but lower than 7 kN (LL_high). Cases, including other LL values, were discarded. A total of 7,020 cases were observed where the occupant used a seat belt with a load-limiting device, in which 3,343 and 3,677 cases had a low and high load-limiting force, respectively. The frontal airbag was deployed in approximately 66.1 % of the cases included.

As for the injuries, only 1.2 % of the occupants considered in the database had a fatal outcome. Almost 17.4% of the occupants sustained MAIS 2+ injuries, and 8.1% sustained MAIS 3+ injuries in any body region. As for thoracic and head injuries, 5.2 % of occupants sustained AIS 2+ injuries in the head and in the thoracic regions, and 3.3 % and 2.0 % sustained AIS 3+ injuries in the thorax and head, respectively.

Table 1
Distribution of variables included in the study.

			Raw cases (N = 14,848)			
			N	%	Mean	SD
Person	Age	years	–	–	39.1	18.2
	Height	cm	–	–	170.6	10.6
	Sex	male	7174	48.3	–	–
	Weight	kg			77.35	19.0
	Driver	yes	12,172	82.0	–	–
Vehicle	Vehicle weight	kg	–	–	1573.0	365.4
	Wheelbase	cm	–	–	279.7	27.4
	Vehicle age at time of crash	years	–	–	5.1	3.6
	Model Year	Range 1990–2015	–	–	2001	5.4
Crash	Longitudinal delta V	km/h	–	–	23.3	12.9
	Direction of principal impact	11	3131	21.1	–	–
		12	8790	59.2	–	–
		1	2927	19.7	–	–
Restrain	Pre-tensioner (presence of a peak)	Lap belt sensor	700	4.7	–	–
		Shoulder belt sensor	5703	38.4	–	–
	Lap belt pre-tensioner TTF (if present)	ms	–	–	16.3	4.3
	Shoulder belt pre-tensioner TTF (if present)	ms	–	–	16.2	3.4
	Lap belt pre-tensioner force (if present)	kN	–	–	1.8	0.6
	Shoulder belt pre-tensioner force (if present)	kN	–	–	1.6	0.5
	Load limiter	Present	7020	47.3	–	–
		Range First stage 0–4.5 kN	3343	22.5	–	–
		Range First stage 4.5–7 kN	3677	24.8	–	–
	Airbag	deployed	9811	66.1	–	–
AIS	Killed		174	1.2		
	Head	2+	779	5.2	–	–
		3+	294	2.0	–	–
	Thorax	2+	767	5.2	–	–
		3+	491	3.3	–	–
	Overall	2+	2588	17.4	–	–
		3+	1204	8.1	–	–

3.2. Multivariate regression analysis

The covariables that were finally retained in the model to estimate the likelihood of fatal, AIS2+ and AIS3+ injuries are shown in Table 2.

3.3. Fatal injury

While the deployment of the airbag was not found significant in the prevention of resulting killed in a crash, the variable showing the interaction between delta-v and airbag deployment was. For each additional km/h, there was a reduction of 2% in the probability of being killed in the collision. Increasing age, weight, and delta-v were also significant predictors of an increased risk of death. Being involved in an oblique collision (11o'clock) was also significantly related to increased risk. The presence of load limiting in the seatbelt was found significant, and while having a lower load-limiter reduced the risk of resulting death by almost 70%, the interaction between delta-v and having a higher value of a load-limiter seatbelt reduced the effect of these seatbelts, especially at higher delta-v's.

3.4. Whole body

The deployment of the airbag was found to increase the risk of sustaining AIS2+ and AIS3+ injuries overall, but this effect needs to be understood with caution as the variable showing the interaction between the airbag and the delta-v was also significant. This interaction points towards a protective effect of the airbag, especially relevant at higher delta-v's. Increasing age, weight, and delta-v were also significantly related to the likelihood of injury. Impact directions that added a slightly lateral direction to the PDOF resulted in increased risk for the occupant for the two injury levels considered. Women were exposed to a greater risk of injury than men for the conditions considered in this study.

When the variables related to the pre-tensioners and load limiters were included in the regression model, the model year of the vehicle was not significant anymore and, therefore, was dropped from the regression model. With respect to restraint systems with no load-limiting characteristics, having a load-limiting seatbelt resulted in a decreased risk of AIS 2+ and AIS3+ injuries, but the effect was controlled by the delta-v. When the load limiter was in the low force category, the seat belt contributed to preventing AIS 3+ injuries, although the significance of the variable was marginal ($p < 0.1$). The model also found that the older the vehicle, the more likely the occupants were to sustain AIS2+ and AIS3+ injuries.

3.5. Thoracic region

As for the thoracic region, again the deployment of the airbag was significantly related to an increased risk of AIS2+ and AIS3+ injuries,

Table 2
Odds ratio (OR) and significance (p) of the independent variables included in the multivariate models to estimate the likelihood of AIS2+ and AIS3+ injuries.

	Fatal injuries		Whole body injuries				Thoracic injuries				Head-face-neck injuries			
			AIS2+		AIS3+		AIS2+		AIS3+		AIS2+		AIS3+	
	OR	p	OR	p	OR	p	OR	p	OR	p	OR	p	OR	p
Airbag deployment (ref: not deployed)	–	–	2.95	***	3.71	***	2.74	***	3.11	***	2.11	***	2.10	*
Age	1.04	***	1.02	***	1.03	***	1.05	***	1.04	***	1.01	***	1.03	***
DoF (ref: frontal)														
1o'clock	–	–	1.28	***	1.28	**	1.51	***	1.50	**	1.22	#	1.40	#
11o'clock	2.04	***	1.35	***	1.53	***	1.69	***	1.88	***	1.50	***	1.93	***
Driver (ref: passenger)	–	–	–	–	0.79	**	0.77	*	0.71	**	–	–	–	–
Delta-v	1.09	***	1.10	***	1.11	***	1.11	***	1.11	***	1.08	***	1.09	***
Height	–	–	–	–		–	–	–	–	–	–	–	–	–
Weight	1.02	***	1.01	***	1.01	***	1.00	*	1.01	**	–	–	–	–
LL level (ref: no LL)														
Low	0.31	*	–	–	0.70	#	–	–	–	–	–	–	–	–
High	0.42	*	–	–	–	–	–	–	–	–	–	–	–	–
Model year	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Lap belt PP (ref: no)	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Shoulder belt PP (ref: no)	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sex (ref: female)	–	–	0.62	***	0.75	***	0.85	#	0.82	#	–	–	–	–
Vehicle age	–	–	1.03	***	–	–	–	–	–	–	–	–	–	–
Vehicle weight	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Vehicle wheelbase	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Airbag*delta-v	0.98	*	0.98	***	0.97	***	0.97	***	0.97	***	0.97	***	0.97	***
LL level*delta-v														
Low	–	–	0.99	**	–	–	–	–	–	–	–	–	–	–
High	1.02	*	0.98	*	–	–	–	–	–	–	–	–	–	–

***p = 0; **p < 0.01; * p < 0.05; # 0.1 ≥ p ≥ 0.05

but there was an interaction between this variable and the delta-v that changed this effect for delta-v above 32.5 km/h and 34.3 km/h for AIS 2+ and AIS 3+ injuries respectively. The effect of age, weight, and delta-v was similar to the one found when the whole body was considered. As also found for the whole-body area, impact directions different from the pure frontal direction contributed to an increased risk of thoracic injuries. It should be noted that the 11o'clock direction, which would be a small overlap or a nearside oblique impact for the driver, resulted consistently in a higher risk of injury than a pure frontal or a far-side oblique impact for the driver. When the focus was on thoracic injuries, being a female occupant was associated with a higher risk of AIS 2+ and AIS 3+ injuries but only with marginal significance ($p < 0.1$). The driver position resulted in a significantly lower risk of injury to the thoracic area.

No other significant effects, including the presence of pre-tensioners and/or load-limiters in the seat belts, were found in the analysis of the risk factors contributing to thoracic injuries.

3.6. Head-face-neck region

Regarding the head-face-neck body region, the deployment of the airbag was also significantly correlated to the existence of AIS2+ and AIS3+ injuries, but again the significant interaction term between airbag deployment and delta-v would revert this relationship above a certain delta-v. Age and delta-v were again significantly related to increasing the likelihood of injuries also in the HFN area. As for the direction of force, it was found consistently that the 11o'clock impact direction was significantly related to the occurrence of head injuries. In the case of HFN, the analysis did not find any significant difference in the injury likelihood between men and women.

4. Discussion

The fitment of advanced restraint systems into the American fleet started to grow linearly from <10% of the vehicles incorporating these features in 1996 to around 80% of the fleet, including pre-tensioners and load limiters circa 2005 (Kent et al. 2007). This growth paralleled the increase in front-end stiffness of passenger cars during the same period, as reported in a review of NCAP tests (Swanson et al., 2003). Since then, the amount of specialized literature showing the benefits of these advanced restraint features in laboratory settings and computational studies has been substantial (Forman et al., 2009; Kent et al., 2001; Michaelson et al., 2008; Forman et al., 2008; Kent et al., 2007; Walz, 2004). It is true that some early field studies also found that force limiters could have been effective in the prevention of severe thoracic trauma in selected real-world crashes (Foret-Bruno et al. 1978). But, to our knowledge, this is the first study using multivariate regression models and including a large sample of real-world cases that assesses the effect of incorporating seat belts with pre-tensioners and load limiters in the likelihood of injuries in the field. If the analysis is restricted to fatal injuries, the presence of a load limiter in the seat belt, regardless of its value, has been found to significantly decrease the risk of death, confirming the results presented in Kahane (2013, 2015) using FARS data.

In this regard, it is relevant to point out that the two variables indicating the presence of pre-tensioners either at the shoulder belt or at the lap belt were not found to be significant in almost any logistic regression model, especially when the focus was on a particular body region. This is probably related to the strong association between the presence of pre-tensioners and load-limiting features in modern vehicles. We chose to keep always, in the models, the variable related to the load-limiting characteristic of the seatbelt even if its VIF was on several occasions above 1.5 (but always smaller than 2), as it was considered especially relevant to understand the effect of advanced restraints on occupants in the field. Further analyses of the influence of pre-tensioners should also consider not only whether there was a pre-tensioner but also the level of pre-tensioning force used. Lower limiting force seat belts were found to decrease the overall risk of AIS 3+ and fatal injuries. Higher limiting force seat belts were effective in the prevention of fatal injuries too. It should be noted that advanced restrained systems are probably optimized for the delta-v used in the NCAP tests (35 mph), while the average delta-v of the NASS CDS sample analyzed in this study is considerably lower (23.3 ± 12.9 km/h). Thus, it is plausible that the effect of advanced seat belts could be greater in high-speed collisions.

The analysis performed here was limited only to frontal impacts, defined as those in which the PDOF ranged between 11 o'clock and 1 o'clock. The results suggest that even if the oblique directionality of the cases included here was minimal, this factor was always significantly associated with an increased risk of AIS 2+ and AIS3+ injuries globally and also when focusing exclusively on the THO and HFN areas. These results agree with those presented in Meyer et al. (2015), although the authors of this study analyzed only a convenience sample of real crashes in which the additional belt spool-out could have been associated with impacts of the occupants against the interior of the vehicles. Again, even though previous studies in the laboratory had shown that pre-tensioners can be effective also in improving how an occupant is restrained in oblique impacts (Lopez-Valdes et al., 2016; Piqueras et al., 2022), this outcome was not found in the current work.

Several recent studies have found that newer vehicles were associated with a reduced risk of injury (Ryb et al., 2011; Thomas, 2013; Klinich et al., 2016; Forman et al., 2019). Forman et al. (2019) found that newer model vehicles (2009 and later) carried less risk of AIS2+ and AIS3+ injuries than older model vehicles. This finding was particularly significant for the lower extremity region and the skull fracture risk. However, their analysis did not find significant reductions in the change of AIS 3+ rib fractures despite all the technological advances implemented in the restraint systems of newer cars. These findings are interestingly related to the results presented here. First, our study did not find the significance of the vehicle model year when the variables related to the presence of pre-tensioners and load limiters were included in the models. Kent et al. (2007) showed a clear correlation between advanced restraint systems and newer vehicles in the NASS CDS sample. In fact, model year was one of the variables that produced a high VIF score in the collinearity checks performed to develop the multivariate models. Second, it results intriguing that the lack of significance of the reduction of AIS 3+ rib fractures found in Forman et al. is somehow paralleled here by finding a marginally significant relationship ($p < 0.1$) between AIS3+ thoracic injuries and the presence of load limiters and pre-tensioners. It is true that the effect of age increasing the risk of thoracic injuries was found to be the largest in the thorax. Therefore, it could be that the negative effect of age might still outperform the benefit of using advanced restraint systems. In any case, the question about why if these advanced seat belt systems have been proven to be so effective in the laboratory setting, their presence is not a significant factor when real-world data are analyzed still needs to be fully answered.

Forman et al. (2019) also pointed out that females continued to be at greater risk than males of AIS 2+ and AIS3+ for most of the injury types considered in their study, as it had already been found by Bose et al. (2011). The latter found that the odds of a belt-restrained female driver sustaining AIS3+ injuries were 47% larger than those of a male driver in comparable crash circumstances. Our study showed similar effects when controlling for age, height, weight, and the amount of seat belt force limiting characteristic that is applied to the occupant, but only when the whole body and thorax were considered. This significance was not observed when the analysis focused on the HFN area. This result suggests that there might be benefits of including pre-tensioners and load limiters in seat belts for other body regions different from the ones analyzed here.

When considered alone, the deployment of airbags was found to increase the risk of AIS2+ and AIS3+ injuries overall significantly and also in the THO and HFN areas. However, an interaction term relating deployment of airbags and delta-v was also included in the models and resulted statistically significant. This term modified the isolated contribution of the airbag, resulting in a protective effect whenever the delta-v of the crash was above a particular speed. To illustrate which would be the delta-v value in which the effect of the airbag would switch from being a risk for thoracic injuries, it was calculated that the speed threshold was slightly above 31 km/h. Fig. 1 shows the relation of the distribution of airbag deployment with delta-v, suggesting the need to check for the interaction between these two variables.

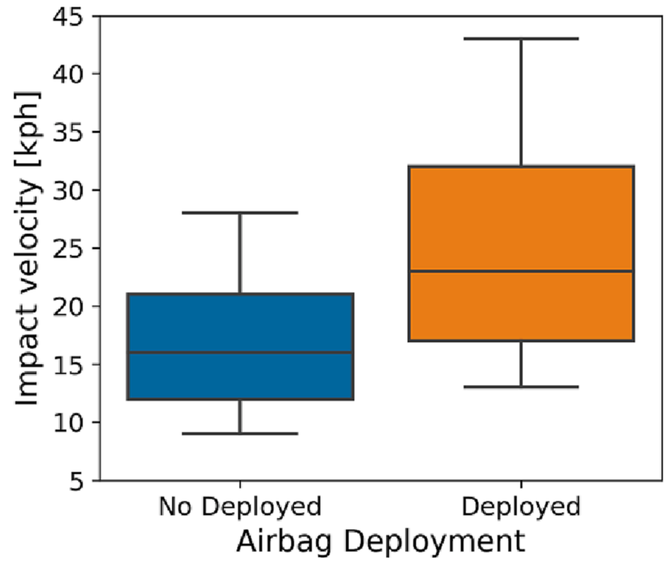

Fig. 1. Box plot showing the distribution of the 10%–90 %ile delta-v values as a function of airbag deployment.

5. Limitations

In the case of seat belts including two-stage load limiters, only the first stage was used in the analyses. This constraint was accepted to avoid having only a few cases in some of the load-limiting categories and as a sensible approach to combine single and dual-stage seat belts into one category. It should be noted that only 4% of the analyzed cases were found to have two-stage load limiters. The use of occupant classification systems (OCS), which affect the response of the restraint systems depending on the size of the occupants, was not considered in this study as seat belt characteristics were identified from NCAP tests performed with a unique dummy size in each occupant position.

It should be noted that the analysis does not incorporate the effect of NASS CDS weighting factors. Despite of it, restricting the sample size to the raw data in NASS CDS resulted in a sample large enough to reach statistical power to detect the significance of several of the independent variables. Even if the use of weighting factors could have help to expand the results to a large sample, since the car model is not included in the calculation of these weighting factors, the process of augmenting the data in NASS CDS to include the load-limiters and pre-tensioner information obtained from the NCAP tests would have been at least questionable. Knowing that our study is missing probably cases with minor injury severity, the estimates of the effects presented here are probably a conservative estimation of the real-world effect of advanced restraint systems.

It is also relevant to note that the WinSmash algorithm used to calculate the delta-v in NASS CDS was updated in 2008 and later. The effects of this update were not uniform but resulted in an average increase of 8% in the estimated delta-v. As indicated by Forman et al. (2019), in a multivariate analysis, the influence of this change would not have been relevant for the estimations of the effect of the other variables in the model.

6. Conclusion

To our knowledge, this is the first time that NASS CDS data are augmented with NHTSA's NCAP data to include specific vehicle information regarding the existence of pre-tensioners and load limiters in the NASS CDS cases. This procedure allowed to run multivariate logistic regression models to estimate the risk of AIS2+ and AIS3+ injuries in the head-face-neck and thoracic areas and in the whole body, including also fatal injuries. The models were developed for the front seat occupants involved in frontal impacts in the NASS CDS database between 2000 and 2015. The presence of pre-tensioners and load limiters with a low load-limiting force (<4.5 kN) was significantly associated with a decreased risk of fatal injuries and AIS3+ in the whole body (OR = 0.31 and OR = 0.70) and load limiters with a higher load-limiting force contributed significantly to reduce fatal injuries (OR = 0.42), although these effects need to be studied in combination with different delta-v values. Controlling for occupant and crash factors, the model predicted a higher risk of injury for women than men. Impacts with slightly oblique components resulted in an increased risk of injury compared to pure frontal impacts, with a clear increased risk of nearside oblique impacts for the driver position. Controlling for the presence of pre-tensioners and load limiters made that the variable model year of the vehicle was not significant in any of the regression models. This study shows that the real-world effectiveness of advanced seat belts still requires further analysis and that other effects like age or impact direction might be more influential in the injury outcome than these seat belt features.

CRediT authorship contribution statement

Manuel Valdano: Conceptualization, Formal analysis, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing. **Jesús Jiménez-Octavio:** Conceptualization, Investigation, Methodology, Resources, Supervision, Writing – review & editing. **Francisco J. Lopez-Valdes:** Conceptualization, Formal analysis, Methodology, Resources, Software, Supervision, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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