Effectiveness of knee airbags across two crash paradigms

July 2019

Samuel S. Monfort
Becky C. Mueller
Insurance Institute for Highway Safety

988 Dairy Road
Ruckersville, VA 22968
+1 434 985 4600

iihs.org

Abstract

Objective: Knee airbags are increasingly common in the fleet, but their performance in real-world crash scenarios remains largely untested. The current study was designed to evaluate the effects of knee airbags in reducing injury rates among drivers involved in a frontal crash.

Method: Analyses were conducted on two datasets. First, data from 414 frontal crash tests were used to calculate injury probability for 12 body regions. Injuries in each of these regions were compared across vehicles with knee airbags and vehicles without them. Second, police-reported crash data were compiled from 14 states and linked to knee airbag status by vehicle make and model. The injury rate for drivers of knee-airbag-equipped vehicles was compared against that for drivers of vehicles without knee airbags.

Results: The presence of knee airbags did not significantly reduce overall injury risk for small or moderate overlap crash tests. In fact, knee airbags in the small overlap tests were associated with elevated injury risk for the upper and lower tibia on the right and left sides. Knee airbags were also associated with increased injury risk for the right femur in these tests, as well as a reduced injury risk for the head. Knee airbags in the moderate overlap tests did not affect injury outcomes for any body region. The police-reported crash data found knee airbags to slightly reduce overall injury risk (from 7.9% to 7.4%), but this effect was not statistically significant after controlling for vehicle weight, model year, and driver characteristics.

Conclusions: The current study suggests that knee airbags do not confer a substantial safety benefit onto drivers. Both in crash tests and real-world crashes, vehicles equipped with knee airbags did not significantly reduce injury risk. Manufacturers should consider the limited safety benefit of knee airbags before expanding their fitment in the fleet.

Keywords: knee airbags; driver safety; injury risk; frontal crashes; crash tests

1.0 Introduction

Knee airbags, which typically deploy from the lower dashboard, are meant to distribute impact forces on a vehicle occupant's lower extremities. They also help reduce forces on an occupant's chest and abdomen by controlling movement of the lower body. Demand for knee airbags has grown in recent years, and market research estimated that approximately half of all 2018 models would be outfitted with at least a driver knee airbag (Transparency Market Research, 2015). Unlike frontal airbags (e.g., Kahane, 2015) and side curtain airbags (e.g., McCartt & Kyrychenko, 2007), the safety benefit of knee airbags in real-world crash events has yet to be empirically demonstrated. Validation of knee airbags is important because—in addition to the cost involved with installing them—injuries to the lower extremities are the most commonly sustained in frontal motor vehicle crashes (Burgess, Dischinger, O'Quinn, & Schmidhauser, 1995; Kuppa, Haffner, Eppinger, & Saunders, 2001; Ye et al., 2015). Lower extremity injuries are also associated with a high-disability risk and substantial societal cost (Castillo, MacKenzie, Wegener, & Bosse, 2006; Read et al., 2002). The current study was therefore designed to assess the extent to which knee airbags reduce the probability of driver injury.

Safety features designed to protect the head and upper body have greatly increased the survivability of high-energy crashes (Braver et al., 2008; Ryb, Dischinger, McGwin, & Griffin, 2011). As a result, the proportion of drivers who might otherwise have been fatally injured from crashes emerge with less severe but potentially debilitating injuries to the lower body. Just as advancements in military safety technology have changed the injury profile of soldiers returning from war (e.g., Okie, 2005), advanced occupant protection systems in passenger vehicles have changed the injury profiles of drivers surviving crashes. Knee airbags may be a countermeasure designed to address rising lower body injury risk.

One reason that limited research exists on the effectiveness of knee airbags pertains to their relatively recent introduction to the fleet. Such research is further limited to crash modes where passenger compartment intrusion is not a primary factor in the injury outcome. As a result, research on the subject has been restricted to small samples or to potentially unrepresentative drivers and vehicle models. For example, older drivers and more expensive vehicles tend to be early adopters of new safety products (Llaneras, 2006), and so research on these populations may not generalize to the wider fleet.

Possibly as a result of the aforementioned limitations, extant research on knee airbags shows limited to mixed safety benefits. Both Patel et al. (2013) and Weaver, Loftis, and Stitzel (2013) found knee airbags to reduce the incidence of thigh and hip fracture but to increase the incidence of tibia and foot fractures. Laboratory tests have found similarly mixed results. Simulated crashes have found knee airbags to reduce both tibia loading (Nie, Crandall, & Panzer, 2017) and the likelihood of occupant submarining (Albert, Beeman, & Kemper, 2018), but sled testing under similar circumstances found that knee airbags may increase forces delivered to the lower body, particularly for out-of-position drivers (Nie et al., 2017; Ye, Panzer, Shaw, & Crandall, 2014). In sum, there remains considerable uncertainty around the true effects of knee airbags in mitigating lower extremity injury risk. The current study was designed to address this uncertainty by analyzing data from crash tests and police-reported crashes. If knee airbags are effective at improving driver safety outcomes, the probability of driver injury—particularly in the lower body—should be reduced in vehicles equipped with them.

2.0 Study 1

Data from controlled frontal crash tests are well-suited for making inferences about how knee airbags affect force delivered to the driver. Because the crash dummy approximates a 50th percentile male driver, comparisons across vehicles are not confounded by driver characteristics that might otherwise confound the relationship between knee airbag fitment and injury risk.

2.1 Method

2.1.1 Data

Data were collected from frontal crash tests conducted at the Insurance Institute for Highway Safety (IIHS) Vehicle Research Center (VRC) in Ruckersville, Virginia. IIHS conducts two different frontal crash tests: a moderate overlap test and a small overlap test. In each test, the vehicle travels at 40 mph (64 km/h) toward a barrier. For the moderate overlap test, 40% of the total width of the vehicle strikes the barrier. For the small overlap test, 25% of the total width of the vehicle strikes the barrier (Figure 1). These data were supplemented with crash test data from vehicle manufacturers submitted through IIHS's verification program. In all, we analyzed 312 moderate overlap tests and 243 small overlap tests.

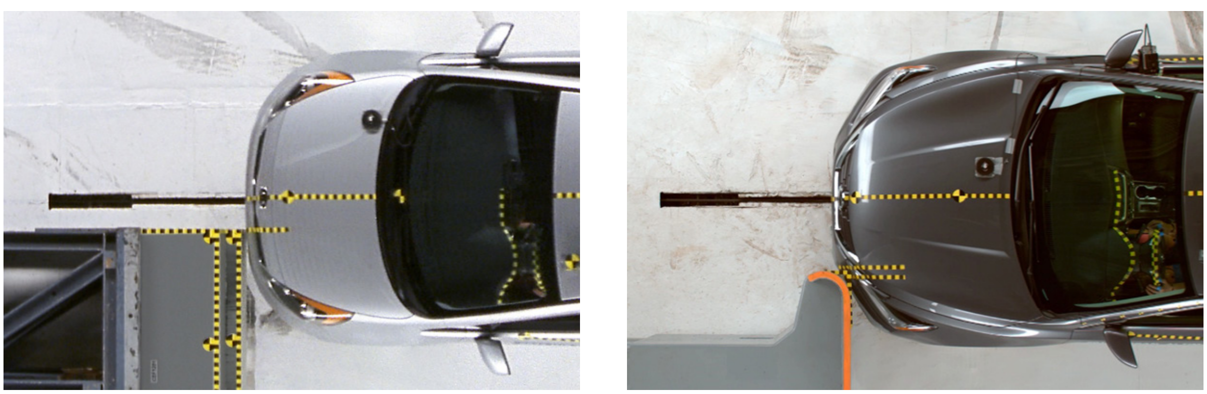

Figure 1. Moderate overlap (left) and small overlap (right) frontal crash tests

Each crash provided sensor data for 12 locations on the dummy: five on each lower extremity (femur, knee, upper tibia, lower tibia, foot), one on the center of the sternum, and one at the center of gravity of the head. Industry-accepted injury risk curves were collected from past research and were applied to dummy sensor measures to determine the probability of injury associated with each body region (Table 1). The injuries modeled by these curves generally corresponded to the region where the sensor was housed (e.g., skull fractures for head sensors), but in some cases the injury risk function represented a broader collection of injuries (e.g., knee-thigh-hip injuries for femur sensors). Where possible, we used injury risk curves for Abbreviated Injury Scale (AIS) ≥ 2, and we assumed driver mass to be 75 kg (i.e., the mass of a 50th percentile adult male). Injury risk was then compared across vehicles with knee airbags and vehicles without them. This comparison was used to evaluate the impact of knee airbags on driver safety during frontal collisions.

There is currently no accepted injury risk curve for knee displacement. Rather than exclude the sensor data for this outcome, we conducted a separate analysis to characterize the effect of knee airbags on this outcome. Although the relationship between knee displacement and injury is not strictly known, we believe that its inclusion in the current analysis is important given the nature of the study (a knee airbag evaluation).

Table 1. Injury risk curve information for each body region included in the current study

Region	Measure	Source	Risk function	Injury outcome
Head	Head Injury Criterion	Eppinger, 1999	$N\left(\frac{\ln(HIC) - 6.96352}{0.84664}\right)$	Skull fracture
Chest	Max. deflection (mm)	Eppinger, 1999	$\frac{1}{1 + e^{(1.8706 - 0.04439 * DMax)}}$	Rib fracture/soft tissue injury
Femur	Force (kN)	Eppinger, 1999	$\frac{1}{1 + e^{(5.795 - 0.5196 * F)}}$	Knee-thigh-hip injury
Upper Tibia	Force (kN)	Kuppa et al., 2001	$\frac{1}{1 + e^{(5.665 - 0.8189 * F)}}$	Tibial plateau/condyle injury
Lower Tibia	Force (kN)	Kuppa et al., 2001	$\frac{1}{1 + e^{(4.572 - 0.6700 * F)}}$	Calcaneus, talus, ankle, and midfoot fracture
Foot	Acceleration (g)	Klopp et al., 1997	$\frac{1}{1 + e^{(2.4401 - 0.0113 * A)}}$	Foot-ankle fracture/ligament tear

2.1.2 Model specification

We assessed the effectiveness of knee airbags using 12 regression models, with knee airbag status, crash test type (small overlap vs. moderate overlap), and their interaction predicting the injury probabilities generated from each sensor. Two of the regression models predicted raw knee displacement rather than injury risk. All outcomes were log transformed to adjust for skewed residuals and *p* values were adjusted using the Benjamini-Hochberg method to control the false discovery rate (Benjamini & Hochberg, 1995). This procedure accounts for the inflated type I error rate that results from multiple significance testing while being somewhat less conservative than a Bonferroni correction. The effect of knee airbags on overall injury risk was also estimated by calculating an overall probability of injury, i.e., the probability of sustaining at least one injury. For the purposes of this calculation, the injury risk functions for each body region were assumed to be independent per the guidelines published by the National Highway Traffic Safety Administration (2008).

The first IIHS consumer rating program was completed in 1995. However, vehicles with knee airbags were relatively rare until around 2011, when advances in airbag technology made knee airbags a feasible option for enhancing frontal crash performance. To avoid an implicit comparison between older and newer vehicles, we restricted our analyses to vehicles of model year 2011 and newer. We also restricted the dataset to the subset of vehicles in our sample with good structure ratings from these tests to avoid effects related to occupant compartment intrusion. Structural intrusion into the occupant's survival space is typically the primary source of lower extremity injury, and knee airbags have limited protective capabilities when the structures behind them are compromised (Rory, 2012; Zuby & Farmer, 1996).

Restricting the sample to tests of newer vehicles with good-rated structures resulted in a final sample size of 309 moderate overlap and 105 small overlap tests. Of the vehicles in these tests, 40 moderate overlap (13%) and 57 small overlap (54%) were equipped with knee airbags.

The vehicles with and without knee airbags were roughly comparable in type and style, with the exception of luxury cars, sports cars, and pickup trucks (Figure 2).

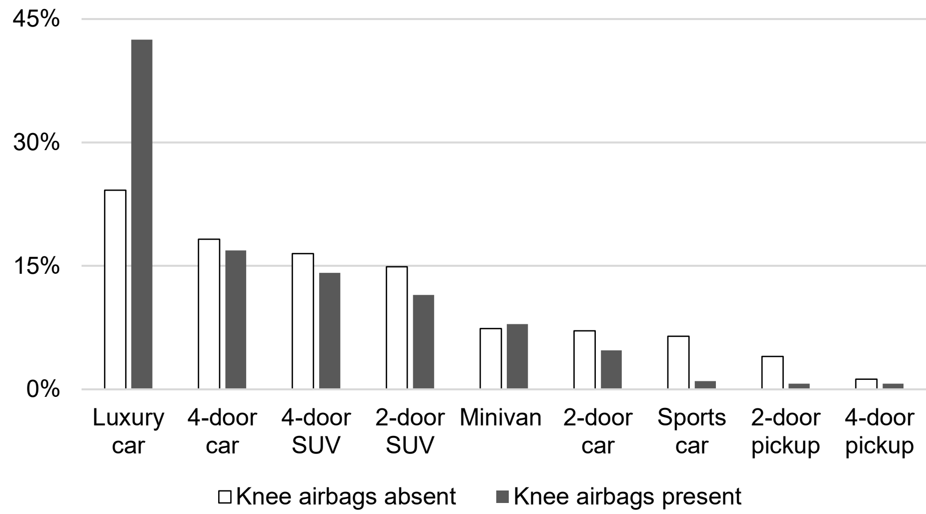

Figure 2. Prevalence of knee airbags among vehicles represented in IIHS frontal crash tests by vehicle type and style; percent values represent each type/style combination as a percent of the knee airbag group

2.2 Results of Study 1

The only statistically significant benefit of knee airbags occurred for the head in the small overlap test. The relative risk of skull fracture for vehicles with knee airbags versus vehicles without knee airbags was estimated as RR = exp(0.324 – 0.936) = 0.542, with 95% confidence limits of 0.335 and 0.877, and a Benjamini-Hochberg adjusted p value of .047 (Table 2). This is equivalent to reducing injury probability from 1.16% to 0.63%.

Table 2. Linear regression results for log of Head Injury Criterion

Parameter	Coefficient	Standard error
Intercept	−3.521	0.0763
Small overlap test	−0.938	0.1956
Knee airbag	0.324	0.2126
Small overlap and knee airbag	−0.936	0.3233

Vehicles with knee airbags were associated with an elevated chance of injury to the lower body during the small overlap frontal crash test. Specifically, knee airbags were associated with higher axial force measurements for the right and left upper and lower tibia sensors, as well as for the right femur. Greater force delivered to the upper tibia in vehicles equipped with knee airbags was associated with an elevated risk of injury to the tibial plateau and condyle for both the right (from 1.1% to 1.7%), RR=1.64, 95% CI [1.18, 2.26], *p*=.014, and left sides (from 1.8% to 2.7%), RR=1.50, 95% CI [1.20, 1.88], *p*=.004. Greater force delivered to the left lower tibia in vehicles equipped with knee airbags was associated with an elevated risk of calcaneus, talus, ankle, and midfoot fractures for both the right (from 2.5% to 3.7%), RR=1.48, 95% CI [1.15, 1.91], *p*=.014, and left sides (from 3.8% to 5.3%), RR=1.38, 95% CI [1.16, 1.65], *p*=.004. Lastly, greater force delivered to the right femur in vehicles equipped with knee airbags was associated with an elevated risk of knee-thigh-hip injury (from 0.380% to 0.516%), RR=1.36, 95% CI [1.11, 1.66], *p*=.014. The change in injury probability associated with having knee airbags was not statistically significant for the other body regions in the small overlap test and was not statistically significant for any body regions in the moderate overlap test. The effect of knee airbags on raw knee displacement was similarly nonsignificant, both for the small overlap test and the moderate overlap test (Table 3). The percent change in the risk of injury for each region and crash mode is depicted in Figure 3.

Table 3. Linear regression results for knee displacement comparison between vehicles with and without knee airbags, by crash test mode

	Test mode	RR	95% CI	*p*
Left knee	Small overlap	1.11	[0.77, 1.61]	.585
	Moderate overlap	0.88	[0.64, 1.21]	.432
Right knee	Small overlap	1.23	[.835, 1.81]	.293
	Moderate overlap	.968	[.728, 1.29]	.820

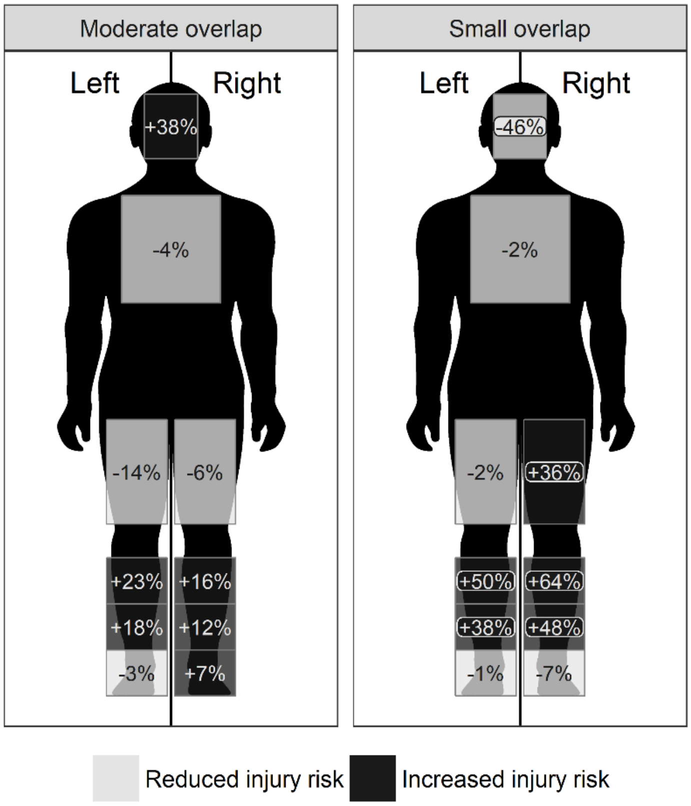

Figure 3. Percent change in likelihood of injury associated with knee airbag fitment during moderate and small overlap crash tests. Reductions in injury risk associated with knee airbag fitment are colored gray; increases in injury risk are colored black. Circled values represent statistically significant ($p < .05$) differences.

Combining each risk estimate into an overall risk estimate (the probability of being injured in at least one body region) found that despite the elevated injury risk to the lower body, the overall risk of injury associated with knee airbags was not significantly different than that associated with no knee airbags, both in the moderate overlap test (66% vs. 65%) RR=1.02, 95% CI [.976, 1.06], p=.460, and in the small overlap test (58% vs. 58%), RR=1.02, 95% CI [.968, 1.07], p=.534. Estimated injury probabilities for small and moderate overlap tests can be seen in Figures 4 and 5, respectively.

In sum, the crash test data suggest that knee airbags do not provide a substantial safety benefit above and beyond other safety features already present in the vehicle, and they may even worsen safety outcomes for the lower body.

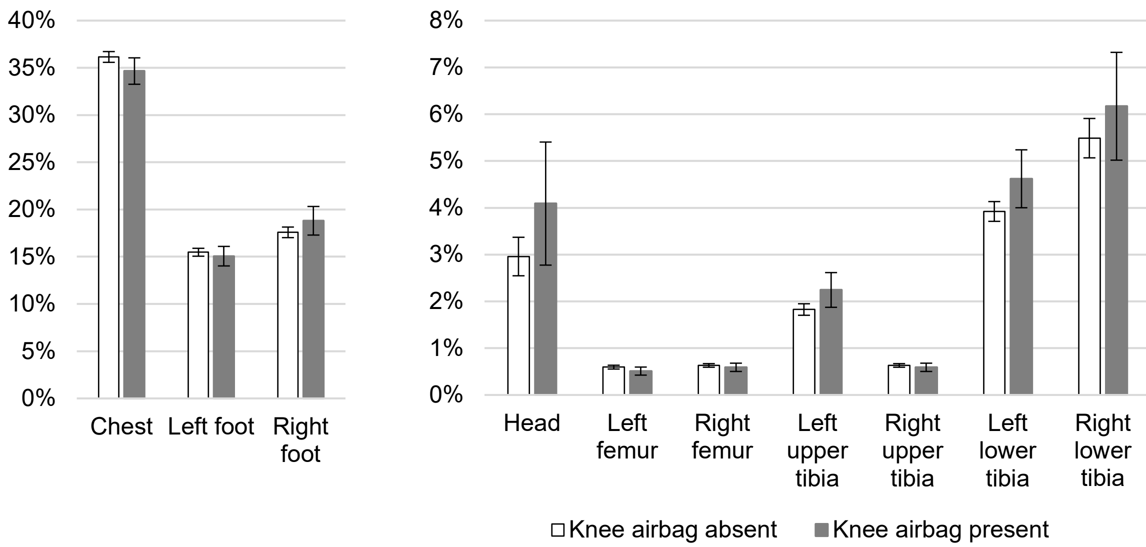

Figure 4. Estimated probability of injury associated with each sensor for vehicles with and without knee airbags during moderate overlap frontal crash tests; error bars represent 95% confidence intervals.

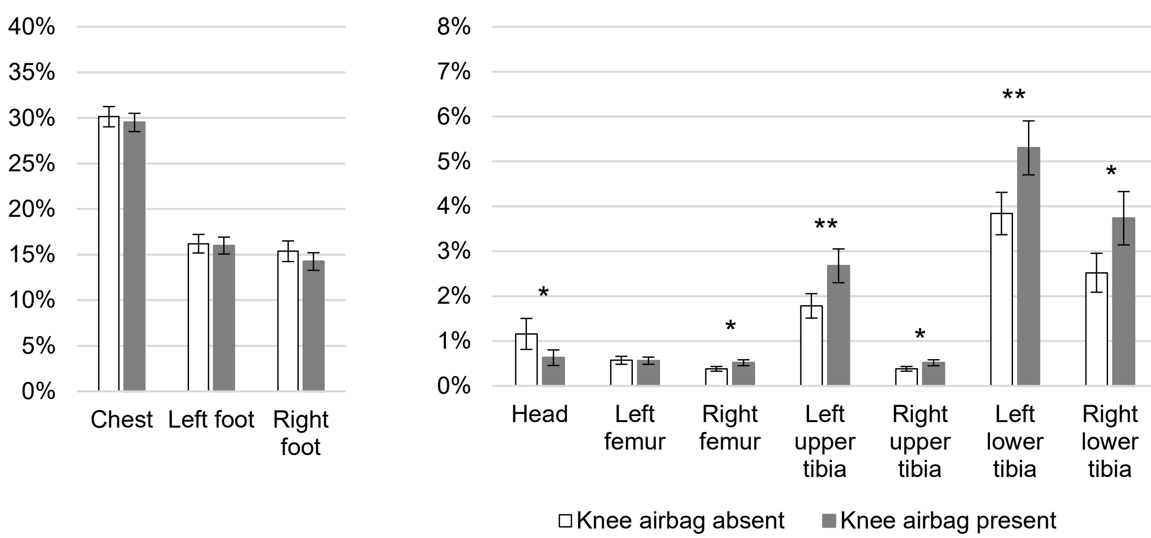

Figure 5. Estimated probability of injury associated with each sensor for vehicles with and without knee airbags during small overlap frontal crash tests; error bars represent 95% confidence intervals; * = $p < .05$; ** = $p < .01$.

3.0 Study 2

For Study 2, crash data were compiled from 14 states and linked to knee airbag status by vehicle make, model, and model year. Conclusions regarding vehicle safety generated from IIHS crash tests have been shown to correspond to death rates in real-world crashes (Farmer, 2005). We therefore hypothesized that the effect of knee airbags on driver injury rates should be relatively small, consistent with its effect on relative injury risk predicted by crash tests.

3.1 Method

3.1.1 Data

Real-world crash data were aggregated from the 14 states that provided sufficiently detailed crash data for the planned analysis. States that did not provide Vehicle Identification Numbers were excluded, because the vehicles in these crashes could not be matched to information indicating the presence of a knee airbag. Data were further reduced to match the filter criteria employed in Study 1. From the initial collection of 22.8 million crashes, just 14,599 were two-vehicle frontal collisions between relatively new vehicles with good-rated structures where knee airbag status was known for both involved. The current study focused on injury outcomes for the drivers in these crashes. Drivers whose injury status was unknown were similarly excluded from the analysis.

Each two-vehicle crash contained one record for each of the drivers involved. Although there was some variation by state in the terminology used to rate injuries, they were coded on a five-point severity scale (i.e., KABCO). However, research suggests that police-reported injury data are not always reliable (Farmer, 2003). To avoid severity-related unreliability, injury information was reduced to a binary outcome. If drivers suffered fatal (K), incapacitating (A), or nonincapacitating (B) injuries, they were coded as “1”. If drivers suffered possible (C) or were not injured (O), they were coded as “0”.

3.1.2 Model specification

We used a conditional logistic regression analysis to model the effect of knee airbags on injury probability. This analysis controls for the effects of unmeasured confounders by comparing the injury outcomes of the drivers involved in the same two-vehicle crash. Extraneous differences that might otherwise differ between injury outcomes—like location of the crash, speed at impact, or time of day—are neutralized. As crashes where both drivers obtained the same injury outcome do not add any relevant information to the comparison, the only crashes retained for the analysis were those where one driver was injured and the other was not. We also included several control variables to help capture injury variability due to driver and crash characteristics: a three-level variable representing risk group status (young, 55+ male, 55+ female) and a continuous weight ratio variable (with higher values corresponding to the subject vehicle being heavier than the partner vehicle).

3.2 Results of Study 2

Vehicles equipped with knee airbags experienced similar injury rates compared with vehicles without them, Exp(B)=.931, 95% CI [.730,1.19], χ^2=.340, p=.560 (Table 4). After accounting for vehicle model year, the weight ratio between crash vehicles, and driver risk status, knee airbags only reduced the probability of driver injury from 7.9% to an estimated 7.4%, a nonsignificant reduction . Therefore, the small beneficial effect of knee airbags observed in the current sample should not be inferred to represent a reliable benefit on real-world crash outcomes.

Table 4. Conditional logistic regression results for driver injury risk predicted by knee airbag status and covariates.

Parameter		Exp(B)	95% CI	*p*
Model year		1.01	[.927, 1.11]	.772
Weight ratio		.327	[.219, .487]	<.001
Driver risk	Young	—	—	—
	55+ Female	2.18	[1.30, 3.67]	.001
	55+ Male	.771	[.468, 1.27]	.018
Knee airbag	No	—	—	—
	Yes	.931	[.730, 1.19]	.560

4. Discussion

The current study was designed to evaluate the effects of knee airbags across two paradigms: for crash test dummies in vehicles striking a static barrier at a fixed speed and for real-world drivers involved in two-vehicle crashes of varying severity. The data from both studies show that knee airbags provide a negligible safety benefit, and that they may even increase injury risk in some cases.

Knee airbags are designed to reduce injuries that occur when forward movement of the occupant results in contact with the vehicle interior, typically the lower instrument panel (Roychoudhury, Conlee, Best, & Schenk, 2004). However, the current study found that knee airbag fitment was associated with greater impact force on the upper and lower tibia sensors in the small overlap test, representing an elevated injury chance to the right and left tibia, ankle, and foot. A paradoxically greater risk for injury to the lower extremities is consistent with preliminary estimates derived from small-samples research (e.g., Weaver et al., 2013). The association between knee airbags and elevated injury risk is far from clear, however. Data from nearly fifteen thousand police-reported crashes in the current study were not detailed enough to isolate injury risk for the lower body, and the observed effect of knee airbags on overall injury risk was not statistically significant.

The marginal effect of knee airbags on injury rates observed in the current study was observed after minimizing the effects of structural intrusion (because vehicles rated poor on this outcome were excluded). When structural intrusion occurs, the forward motion of the occupant is met by a shrinking occupant space, which reduces the opportunity for airbags to absorb the occupant's kinetic energy. As a result, injuries from such crashes tend to be those that knee airbags are not designed to mitigate (Ohachi, Masuda, Katsumata, & Kanno, 2012; Ye et al., 2014). However, some research suggests that knee airbags may be beneficial in a subset of intrusion cases. Roychoudhury et al. (2004) suggest that knee airbags may mitigate injuries resulting from toe pan intrusion by preventing knee contact injuries. The current study did not observe this effect in the knee displacement data, but the impact of knee airbags on knee displacement should be examined again once injury risk curves for this outcome are established.

Informal discussions with vehicle manufacturers at the Insurance Institute for Highway Safety (IIHS) Vehicle Research Center (VRC) suggest that a primary motivation for fitting knee airbags is to aid meeting unbelted occupant protection requirements prescribed in Federal Motor Vehicle Safety Standards. Knee airbags augment the restraining forces from the main airbags by providing a lower load path through the femurs of the test dummy with an additional load path during the unbelted crash tests. The femur forces, which are moderated by the knee airbags, ostensibly make up for the lack of lower body restraint that otherwise would be provided by the lap belt. Vehicles designed for the European market, where unbelted testing is not required, are often adapted for sale in the United States by adding knee airbags. Although our analyses did not test the potential benefits of knee airbags for unbelted occupants, it is possible that the lower head injury risk observed in IIHS crash tests resulted from reduced occupant forward motion, a mechanism that may also benefit real unbelted occupants.

5.0 Conclusion

The current study found that knee airbags are not associated with a substantial safety benefit. In two test paradigms, vehicles with knee airbags were either associated with slightly worse injury outcomes or injury outcomes that were not significantly different compared with vehicles not equipped with them. These findings arose independent of other confounding factors, such as structural intrusion, driver demographics, and crash characteristics. In sum, the data do not present a clear benefit of knee airbags for injury risk; it seems likely that their true effect on driver safety is negligible.

6.0 Acknowledgment

This work was supported by the Insurance Institute for Highway Safety.

7.0 References

Albert, D.L., Beeman, S.M., & Kemper, A.R. (2018). Occupant kinematics of the Hybrid III, THOR-M, and postmortem human surrogates under various restraint conditions in full-scale frontal sled tests. *Traffic Injury Prevention*, *19*(1), S50–S58.

Benjamini, Y. & Hochberg, Y. (1995). Controlling the false discovery rate: A practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society*, *57*(1), 289–300.

Braver, E.R., Kufera, J.A., Alexander, M.T., Scerbo, M., Volpini, K., & Lloyd, J.P. (2008). Using head-on collisions to compare risk of driver death by frontal air bag generation: A matched-pair cohort study. *American Journal of Epidemiology*, *167*(5), 546–552.

Burgess, A.R., Dischinger, P.C., O'Quinn, T.D., & Schmidhauser, C.B. (1995). Lower extremity injuries in drivers of airbag-equipped automobiles: Clinical and crash reconstruction correlations. *The Journal of Trauma: Injury, Infection, and Critical Care*, *38*(4), 509–516.

Castillo, R.C., MacKenzie, E.J., Wegener, S.T., & Bosse, M.J. (2006). Prevalence of chronic pain seven years following limb threatening lower extremity trauma. *Pain*, *124*, 321–329. doi: 10.1016/j.pain.2006.04.020

Eppinger, R., Sun, E., Bandak, F., Haffner, M., Khaewpong, N., Maltese, M., ... & Saul, R. (1999). *Development of improved injury criteria for the assessment of advanced automotive restraint systems-II*. National Highway Traffic Safety Administration: Washington, DC.

Farmer, C.M. (2003). Reliability of police-reported information for determining crash and injury severity. *Traffic Injury Prevention*, *4*(1), 38–44.

Farmer, C.M. (2005). Relationships of frontal offset crash test results to real-world driver fatality rates. *Traffic Injury Prevention*, *6*(1), 31–37.

Kahane, C.J. (2015). Lives saved by vehicle safety technologies and associated Federal Motor Vehicle Safety Standards, 1960 to 2012—passenger cars and LTVs (Report No. DOT HS-812-069). Washington, DC: National Highway Traffic Safety Administration.

Klopp, G. S., Crandall, J. R, Hall, G. W., Pilkey, W. D., & Hutwitz, S. R. (1997). Mechanisms of injury and injury criteria for the human foot and ankle in dynamic impacts to the foot. *Proceedings of the 1997 IRCOBI Conference*, 73–86.

Kuppa, S., Haffner, M., Eppinger, R., & Saunders, J. (2001). *Lower extremity response and trauma assessment using the Thor-Lx/HIIIr and the Denton leg in frontal offset vehicle crashes* (No. 2001-06-0161). SAE Technical Paper.

Llaneras, R.E. (2006). Exploratory study of early adopters, safety-related driving with advance technologies. *The National Academies of Sciences, Engineering, and Medicine*, X, 1–162.

McCartt, A.T. & Kyrychenko, S.Y. (2007). Efficacy of side airbags in reducing driver deaths in driver-side car and SUV collisions. *Traffic Injury Prevention*, *8*(2), 162–170.

National Highway Traffic Safety Administration. (2008). Consumer information; New car assessment program, *Federal Register*, *73*(134), 40016–40050.

Nie, B., Crandall, J. R. & Panzer, M.B. (2017). Computational investigation of the effects of knee airbag design on the interaction with occupant lower extremity in frontal and oblique impacts. *Traffic Injury Prevention*, *18*(2), 207–215.

Ohachi, J., Masuda, M., Katsumata, S., & Kanno, Y. (2012). *Consideration of protection effects with knee airbag by the simulation of frontal impact and the analysis of traffic accident data JSAE* (Paper No. 20125279). Warrendale, PA: SAE International.

Okie, S. (2005). Traumatic brain injury in the war zone. *The New England Journal of Medicine*, *352*, 2043–2047. doi:10.1056/NEJMp058102

Patel, V., Griffin, R., Eberhardt, A.W., McGwin Jr., G. (2013). The association between knee airbag deployment and knee-thigh-hip fracture injury risk in motor vehicle collisions: A matched cohort study. *Accident Analysis and Prevention*, *50*, 964–967.

Read, K. M., Burgess, A. R., Dischinger, P. C., Kufera, J. A., Kerns, T. J., Ho, S. M., & Burch, C. (2002). Psychosocial and physical factors associated with lower extremity injury. *Annual Proceedings/Association for the Advancement of Automotive Medicine*, 46, 289–303.

Rory, A. (2012). Lower extremity injuries and intrusion in frontal crashes. *Accident Reconstruction Journal*, *23*(4), 1–23.

Roychoudhury, R.S., Conlee, J.K., Best, M., & Schenk, D. (2004). Blow-molded plastic active knee bolsters (Paper 2004-01-0844), *2004 SAE World Congress*, Detroit, MI: SAE International.

Ryb, G.E., Dischinger, P.C., McGwin, G., & Griffin, R.L. (2011). Crash-related mortality and model year: Are newer vehicles safer? *Annals of Advances in Automotive Medicine*, *55*, 113–121.

Transparency Market Research. (2015). *Automotive airbag market—Global industry analysis, size, share, growth, trends and forecast 2014–2020*. Retrieved from https://www.transparencymarketresearch.com/automotive-airbag-market.html

Weaver, A.A., Loftis, K.L., & Stitzel, J.D. (2013). Investigation of the safety effects of knee bolster air bag deployment in similar real-world crash comparisons. *Traffic Injury Prevention*, *14*(2), 168–180. doi:10.1080/15389588.2012.697643

Ye, X., Panzer, M.B., Shaw, G., & Crandall, J.R. (2014). Driver lower extremity response to out of position knee airbag deployment. *Proceedings of the 2014 IRCOBI Conference*, *14*(27), 198–212.

Ye, X., Poplin, G., Bose, D., Forbes, A., Hurwitz, S., Shaw, G., & Crandall, J. (2015). Analysis of crash parameters and driver characteristics associated with lower limb injury. *Accident Analysis & Prevention*, *83*, 37–46.

Zuby, D.S. & Farmer, C.M. (1996). Lower extremity loads in offset frontal crashes. *Proceedings of the International Technical Conference on the Enhanced Safety of Vehicles*. National Highway Traffic Safety Administration, 414–421.