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16. Abstract
Previous studies have shown that lower extremity injuries account for a significant portion of the injuries sustained by passenger vehicle drivers in frontal crashes, and this pattern continues to hold for newer model year vehicles. This paper explores the potential causal factors associated with the risk of moderate or more severe lower extremity injuries in frontal crashes with a particular emphasis on the role of intrusion. A categorical analysis of the relationship between floor and toe pan intrusion showed that higher levels of intrusion were related to a larger percentage of lower leg injuries. A categorical analysis of the relationship between instrument panel and knee bolster intrusion and upper leg injuries was less clear but still demonstrated that vehicles with any intrusion had a higher percentage of upper leg injuries than vehicles with no intrusion. Logistic regression models were used to estimate the independent effect of intrusion on the probability of lower extremity injuries while controlling for crash severity (change in velocity), age, gender, body mass index, vehicle age and vehicle body type. The results indicated that for all frontal crashes the odds of experiencing a lower leg injury when floor or toe pan intrusion occurred were twice the odds of experiencing a similar injury without intrusion. In full frontal crashes and in left offset and small overlap impact crashes, the lower leg injury odds ratios for intrusion versus no intrusion increased to seven. For all frontal crashes the odds of experiencing an upper leg injury when instrument panel or knee bolster intrusion occurred were four times the odds of experiencing a similar injury without intrusion. The upper leg injury odds ratios for intrusion versus no intrusion increased to eight in full frontal crashes and to 17 in left offset and small overlap impact crashes.

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NASS-CDS, frontal crashes, offset, injuries, lower extremity, leg

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EXECUTIVE SUMMARY

Previous studies have shown that lower extremity injuries account for a significant portion of the injuries sustained by passenger vehicle drivers in frontal crashes, and this pattern continues to hold for newer model year vehicles. This paper explores the factors associated with the risk of moderate or more severe lower extremity injuries in frontal crashes with a particular emphasis on the role of intrusion.

An examination of the moderate or more severe lower leg injuries experienced by these drivers revealed that the floor or foot control was the source of an estimated 93 percent of the injuries. A similar examination of upper leg injuries found that the instrument panel or knee bolster was the source of an estimated 87 percent of the injuries. Overall an estimated 3.5 percent of belted drivers of model year 1998 through 2010 vehicles in frontal crashes where the vehicle was towed due to damage experienced a lower leg injury of moderate or higher severity from the floor or foot control, and 1.5 percent experienced an upper leg injury of moderate or more severity from the instrument panel or knee bolster.

Based upon these results, this report focused on injuries from these sources and intrusion of the floor, toe pan, instrument panel and knee bolster. Floor and toe pan intrusion into the driver's seating position occurred in an estimated 2 percent of all vehicles in frontal crashes. Among frontal damage types, floor and toe pan intrusion was most likely to occur in a left side small overlap impact (SOI) at an estimated 6 percent. Instrument panel and knee bolster intrusion into the driver's seating position occurred in an estimated 3 percent of all vehicles in frontal crashes with intrusion most likely to occur in left offsets at an estimated 8 percent.

A categorical analysis of the relationship between floor and toe pan intrusion showed that higher levels of intrusion were related to a larger percentage of lower leg injuries. A categorical analysis of the relationship between instrument panel and knee bolster intrusion and upper leg injuries was less clear but still demonstrated that vehicles with any intrusion had a higher percentage of upper leg injuries than vehicles with no intrusion.

Logistic regression models were used to estimate the independent effect of intrusion on the probability of lower extremity injuries while controlling for crash severity (delta-V), age, gender, body mass index, vehicle age and vehicle body type. A total of twelve statistical models were estimated based upon two dependent variables (lower leg injuries and upper leg injuries), two measures of intrusion (continuous intrusion measures and an indicator variable for the presence of intrusion), and three damage types (all frontals, full frontals, and left offset and SOI).

Overall the results from the logistic models indicated a statistically significant positive effect of intrusion on the likelihood of lower extremity injuries even when controlling for delta-V as well as driver and vehicle characteristics. The results indicated that for all frontal crashes the odds of experiencing a lower leg injury when floor or toe pan intrusion occurred were twice the odds of experiencing a similar injury without intrusion. In full frontal crashes and left offset and SOI crashes, the lower leg injury odds ratios for intrusion versus no intrusion increased to seven. Furthermore, the models indicated that each additional centimeter of intrusion increased the odds of lower leg injury by an estimated 14 percent in full frontals and 5 percent in left offset and SOI crashes. Overall the odds of experiencing an upper leg injury when instrument panel or knee bolster intrusion occurred were four times the odds of experiencing a similar injury without intrusion. The upper leg injury odds ratios for intrusion versus no intrusion increased to eight in full frontal crashes and to 17 in left offset and SOI crashes. The models also indicated that each additional centimeter of intrusion increased the odds of upper leg injury by about 5 percent in these two damage types.

1. INTRODUCTION

Previous studies have shown that lower extremity injuries account for a significant portion of the injuries sustained by passenger vehicle drivers in frontal crashes (Kuppa et al. 2001), and this pattern continues to hold for newer model year vehicles. According to the 2009 National Automotive Sampling System – Crashworthiness Data System (NASS-CDS), an estimated 37 percent of the moderate or more severe injuries experienced by drivers of model year 2003 through 2010 passenger vehicles towed due to damage in frontal crashes affect the lower extremities. An estimated 26 percent of the serious or more severe injuries to this same group affect the lower extremities. Furthermore, since many of these injuries are not life-threatening, their severity as measured on the Abbreviated Injury Scale (AIS) may not fully reflect the physical disabilities and psychological effects of these injuries (Read et al. 2004). This paper explores the potential causal factors associated with the risk of moderate or more severe lower extremity injuries in frontal crashes with a particular emphasis on the role of intrusion.

Understanding the role of intrusion in predicting lower extremity injuries is complicated because of the large number of possible explanatory factors. In an overview of lower extremity injuries in frontal crashes, Rudd (2009) found that the risk of leg, ankle, and foot injuries generally increased with higher levels of toe pan intrusion. However, in additional to toe pan intrusion, Rudd also considered both characteristics of the occupants such as age, gender, height and seating position as well as characteristics of the vehicles such as body type (passenger car versus light truck and van), model year, frontal damage type (offset versus full frontal), and crash severity as measured by the change in velocity (delta-V). Rudd implicitly controlled for restraint use by only examining properly belted occupants. All of these variables are available in the NASS-CDS, and this report considers many of the same factors.

While toe pan intrusion has been correlated with lower extremity injuries in previous studies (Eigen & Glassbrenner 2003, Crandall et al. 1995), this report takes a more broad view. The analysis first explores the vehicle components that are the most common source of lower extremity injuries and then estimates the relationship between intrusion of these components and the risk of injury. However, since the role of intrusion in lower extremity injuries is complicated by the fact that crash severity is correlated with intrusion as well as injury risk, a multivariate statistical model containing intrusion in addition to other factors also is presented to separate out the independent contribution of intrusion.

There are some factors that have been shown to be correlated with the risk of foot and ankle injuries that are not considered in this study including foot placement, size of foot and type of shoe (Crandall et al. 1996). While these factors may be important for completely understanding the causal mechanism, the primary purpose of this report is to test whether intrusion is correlated with lower extremity injuries. The consideration of additional factors is intended primarily to control for and rule out competing explanations; it is not meant to provide a complete explanation of the injury mechanism.

A second consideration is that the effect of intrusion may be conditional on frontal damage type. Intrusion may be more important in some frontal damage types than in others, and the relationship between intrusion and lower extremity injuries may be obscured by combining all frontal damage types. Therefore this report explores this possibility by presenting results for all frontal damage types as well as for particular subsets of frontal crashes.

2. APPROACH AND DATA

Crashes included in this analysis are a subset of the NASS-CDS sample from 1997 through 2009. The vehicles selected were passenger vehicles towed due to damage of model year 1998 through 2010. The vehicles were inspected by a NASS-CDS researcher and were not involved in a rollover. For most of the vehicles, the general area of damage of the highest deformation location was the front. However, some cases with a general area of damage of right or left were included because they fit the Medical College of Wisconsin definition of a frontal small overlap impact (SOI), which uses the Collision Deformation Classification and crush profiles (Halloway et al. 2011). Frontal impact crashes that were not SOIs were classified according to the width and location of the direct damage into either right or left frontal offset, full frontal or center damage modes. Direct damage that encompassed and likely engaged both frame rails based upon the average location of the rails for the vehicle class were classified as full frontal damage. Direct damage that covered only one frame rail was identified as an offset, and direct damage that occurred between the two frame rails was considered center damage. [1]

Also, the vehicle had to have a known total delta-V to control for crash severity. Finally, to avoid the possible influence of an extreme outlier, one case with a total change of velocity of 155 kilometers per hour was excluded since it was over 25 kph greater than the next highest value. After applying all of these vehicle restrictions, there were 10,424 vehicles.

To simplify the analysis of injuries and to control for seating position, only the driver was examined, and a handful of cases were dropped because the driver seat was not on the left of the vehicle. Drivers had to be restrained by three-point belts and have known injury outcomes, age, height, and weight. [2] Age was used for predicting the probability of a lower extremity injury in the statistical models, and height and weight were needed to compute the body mass index (BMI), which was also a predictor in the statistical models.

Descriptive statistics for the above variables revealed that a few cases had extreme values. Cases with extreme values were excluded to avoid possible outliers from having a usually large effect on the statistical results. Drivers younger than 16 years old and ones with a calculated BMI of less than 16 or greater than 50 were excluded. Many of the unusually low and high BMI values appeared to involve incorrectly recorded weights or heights, but it was not possible to determine definitely which values, if any, were incorrect. Therefore, the decision was made to exclude drivers identified as severely underweight or severely obese based upon the calculated BMI.

The final data set for analysis contained 7,284 vehicles and drivers involved in 6,938 crashes. Overall, an estimated 52 percent of the drivers were women. The vehicle body types were an estimated 66 percent passenger cars and the remainder were LTVs (light trucks and vans). The 34 percent that were LTVs included an estimated 16 percent utility vehicles, 7 percent vans, and 11 percent pickups. Table 1 provides summary statistics for the other variables used in this report.

[1] A total of 45 vehicles with frontal damage were dropped from the analysis because they could not be classified, usually because they had direct damage outside of the frame rails but crush on both corners and thus did not fit any of the defined damage types.
[2] A total of 236 drivers in model year 1998 and 1999 vehicles from the 2009 file were not included because it was the first year NASS-CDS began restricting collection of injury outcomes to occupants of vehicles ten years old or newer.

Table 1: Descriptive Statistics for Possible Predictors of Lower Extremity Injuries

	Weighted Average	Minimum	Maximum
Total delta-V (kph)	21	5	129
Model Year	2001	1998	2010
Age of Driver	37	16	97
BMI of Driver (kg/m^2)	26.2	16.1	50.0

Source: NASS-CDS 1997-2009; weighted total = 2,753,917; sample size = 7,284

Table 2 provides an overview of the types of frontal damage included in the analysis based upon the classification described above. The most frequent frontal damage type in the report is a full frontal crash, where it is likely that the crash engaged both frame rails, and this type accounts for an estimated 42 percent of the vehicles. The second most frequent frontal damage type is a left offset, where it is likely that the crash engaged the frame rail on the driver's (left) side of the vehicle, for an estimated 20 percent. A left SOI, where the crash occurred on the driver's side and likely did not engage any frame rails, accounted for an estimated 10 percent. The least frequent type of damage, accounting for an estimated 3 percent of the vehicles, was center damage likely to be a collision with a narrow object between the two frame rails.

Table 2: Frontal Damage Types

Damage Type	Weighted Percent
Center	3%
Full Frontal	42%
Left Offset	20%
Left Small Overlap Impact (SOI)	10%
Right Offset	17%
Right Small Overlap Impact (SOI)	8%
Total	*100%*

Source: NASS-CDS 1997-2009; weighted total = 2,753,917; sample size = 7,284

3. LOWER EXTREMITY INJURIES

Lower extremity injuries in this analysis were divided into lower and upper leg injuries. Lower leg injuries involve the foot and the leg below the knee; upper leg injuries involve the knee, thigh and pelvis. The regions of lower and upper leg were assigned based upon the body region codes of the Abbreviated Injury Scale-85 (AIS-85). While NASS-CDS coded the injuries using AIS-90, the body region codes in AIS-90 do not separate upper and lower leg injuries. Instead, AIS-90 body region codes only indicate "lower extremity." NASS-CDS, however, also provides the AIS-85 body region that is derived from AIS-90 injury coding. The derived AIS-85 body regions that were relevant for this analysis were ankle/foot, knee, leg (lower), lower limb(s) (whole or part unknown), pelvic/hip and thigh.[3]

The 7,284 drivers in the sample had a total of 1,577 injuries of AIS severity moderate (2) or higher involving the six body regions identified above of which only the 74 listed as "lower limb(s) (whole or part unknown)" did not provide enough information to differentiate between upper and lower leg. Two approaches were adopted to assign these injuries to either upper or lower leg. One method was to use the body region assigned to lower extremity skeletal injuries based upon the complete AIS-90 injury code used in Rudd (2009), which was used to assign 44 of the 74 injuries. A second method involved

[3] While the derived AIS-85 body region was used for classification into upper or lower leg injuries, the AIS-90 coding was used for severity.

reviewing all of the lower extremity injuries. In the 30 reviewed cases, the injury was assigned to upper or lower leg based upon clinical review.[4]

Once all the 1,577 injuries were assigned to either the upper or lower leg, only upper and lower leg injuries at the maximum AIS severity for each leg region were retained for analysis. For example, if a driver had an AIS 2 (moderate) foot/ankle injury, an AIS 2 (moderate) knee injury and an AIS 3 (serious) thigh injury, then the AIS 2 foot/ankle injury was retained as the maximum lower leg injury and the AIS 3 thigh injury was retained as the maximum upper leg injury. Overall, this selection process produced 768 lower leg injuries and 434 upper leg injuries. The remaining 375 lower extremity injuries were dropped because there was a more severe injury for the same leg region.

The next step in the analysis involved determining the component that was the source of the injury. Table 3 contains the relative frequency of components listed as the injury source of the maximum AIS (MAIS) 2 and greater lower leg injuries.

Table 3: Injury Source for MAIS 2+ Lower Leg Injuries

Injury Source Component	**Weighted Percent of Injuries**
Floor (Including Toe Pan)	68.0%
Foot Controls Including Parking Brake	25.2%
Instrument Panel and Knee Bolster	5.7%
All Other	1.1%
Total	*100.0%*

Source: NASS-CDS 1997-2009, weighted total = 144,243, sample size = 768

Table 3 indicates that the floor, toe pan and foot controls were the source of an estimated 93 percent of the moderate or more severe injuries to the lower leg including the foot and ankle. The instrument panel and knee bolster accounted for an estimated 6 percent, and no other component accounted for more than 1 percent. The remainder of this analysis focuses on injuries where floor or foot controls was listed as the injury source.

Table 4 demonstrates that an estimated 3.5 percent of drivers in this analysis experienced a moderate or more severe lower leg injury from floor or foot controls. Among the 3.5 percent who experienced such injuries, most of the drivers experienced moderate injuries although a few serious injuries occurred.

Table 4: Presence and Severity of Lower Leg Injuries from Floor or Foot Controls

Injury Severity	**Weighted Percent of Drivers**
No MAIS 2+ Injury	96.5%
MAIS 2: Moderate	3.3%
MAIS 3: Serious	0.2%
Total	*100.0%*

Source: NASS-CDS 1997-2009; weighted total = 2,753,917; sample size = 7,284

[4] The clinical review was completed by NHTSA's Human Injury Research Division.

Table 5 contains the relative frequency of components listed as the injury source of the MAIS 2 and greater upper leg injuries. Table 5 indicates that the instrument panel and knee bolster are the source of 87 percent of the moderate or more severe injuries to the upper leg including the knee, thigh and pelvis.[5] The remaining injuries were split among a variety of different components. The remainder of this analysis is focused on injuries where the instrument panel or knee bolster was listed as the injury source.

Table 5: Injury Source for MAIS 2+ Upper Leg Injuries

Injury Source Component	**Weighted Percent of Injuries**
Instrument Panel and Knee Bolster	87.4%
Left Hardware	4.2%
Left Interior	1.8%
Floor (Including Toe Pan)	1.8%
Floor or Console Transmission Lever	1.4%
Steering Wheel	1.1%
All Others	2.3%
Total	*100.0%*

Source: NASS-CDS 1997-2009, weighted total = 53,301, sample size = 434

Table 6 demonstrates that an estimated 1.5 percent of drivers in this analysis experienced a moderate or more severe upper leg injury from the instrument panel or knee bolster. Among the 1.5 percent who experienced such an injury, most of the drivers experienced moderate injuries although a few serious and severe injuries occurred. (More details regarding the lower and upper leg injury counts may be found in Table 14 in the Appendix.)

Table 6: **Presence and Severity of Upper Leg Injuries From Instrument Panel/Knee Bolster**

Injury Severity	**Weighted Percent of Drivers**
No MAIS 2+ injury	98.5%
MAIS 2: Moderate	1.1%
MAIS 3: Serious	0.4%
MAIS 4: Severe	<0.1%
Total	*100.0%*

Source: NASS-CDS 1997-2009; weighted total = 2,753,917; sample size = 7,284

4. INTRUSION

The previous section demonstrated that the components most likely to be associated with lower extremity injuries are the floor and foot controls for lower leg injuries and the instrument panel and knee bolster for upper leg injuries. Therefore, the intruding components associated with these injury sources were selected for further study. For lower leg injuries, the intruding components of interest were the floor pan

[5] The components of instrument panel and knee bolster were combined for all years of NASS-CDS because they share the same component code in some of the years.

(including sill) and the toe pan. For upper leg injuries, the intruding component of interest was the instrument panel and knee bolster.

To compute the level of intrusion, all intrusions of the floor pan, toe pan, instrument panel and knee bolster assigned to the front left (driver) seat were selected. For 6,802 vehicles, there was no intrusion of the floor or toe pan of three centimeters (cm) or greater assigned to the driver's seating position.[6] In 450 cases the maximum floor or toe pan intrusion, ranging from 3 to 106 cm, was retained. For the remaining 32 vehicles, the maximum intrusion was a range rather than an exact measure. In these cases the measure of intrusion was imputed by replacing the range with the estimated average intrusion of known values within the same range. Similarly, for 6,969 vehicles, there was no relevant intrusion of the instrument panel or knee bolster. In 280 cases the maximum instrument panel or knee bolster intrusion, ranging from 3 to 92 cm, was retained. For the remaining 35 vehicles, the maximum intrusion was imputed by replacing the range with the estimated average.

Table 7 contains estimates of the percent of vehicles with relevant intrusion, and Table 8 reports the amount of intrusion when it occurs. Overall, floor or toe pan and instrument panel or knee bolster intrusion into the drivers' seating positions are relatively rare in frontal crashes. Floor or toe pan intrusion occurred in an estimated 2 percent of the towed vehicles with frontal damage, and instrument panel or knee bolster intrusion occurred in an estimated 3 percent of the vehicles. Table 7 also demonstrates that intrusion is related to the frontal damage type with collisions on the right side of the vehicle rarely resulting in relevant intrusions for the driver's seating position. The frontal damage type most likely to have floor or toe pan intrusion is a left small overlap impact, and the type most likely to have instrument panel or knee bolster intrusion is a left offset crash. The second most common type of frontal damage with floor or toe pan and instrument panel or knee bolster intrusion was a center crash where the damage was concentrated between the two frame rails. When intrusion does occur, Table 8 shows that the largest estimated floor or toe pan intrusion occurs with center and left offset damage, and the largest estimated instrument or knee panel intrusion occurs with left offset damage.

Table 7: **Presence of Intrusion by Damage Type**

Damage Type	Weighted Percent With Floor or Toe Pan Intrusion	Weighted Percent With Instrument Panel or Knee Bolster Intrusion	Sample Size
Center	5%	4%	358
Full Frontal	1%	1%	3,078
Left Offset	3%	8%	1,325
Left SOI	6%	2%	751
Right Offset/SOI[7]	<1%	<1%	1,772
Total	*2%*	*3%*	*7,284*

Source: NASS-CDS 1997-2009; weighted total = 2,753,917

[6] NASS-CDS data collection rules do not require the coding of intrusions of 2 cm or less, which is approximately less than 1 inch.
[7] Right offset and SOI are combined due to the small number of cases of intrusion in each category.

Table 8: **Magnitude of Intrusion by Damage Type**

Damage Type	Weighted Average Floor or Toe Pan Intrusion When It Occurs (cm)	Sample Size With Intrusion	Weighted Average Instrument Panel or Knee Bolster Intrusion When It Occurs (cm)	Sample Size With Intrusion
Center	17	61	13	45
Full Frontal	12	156	11	96
Left Offset	16	134	40	81
Left SOI	12	104	13	61
Right Offset/SOI[5]	6	27	7	32
Total	*13*	*482*	*30*	*315*

Source: NASS-CDS 1997-2009; weighted total (floor/toe pan intrusion) = 57,764; weighted total (instrument panel/knee bolster intrusion) = 69,864

5. INTRUSION, DELTA-V AND INJURY: SIMPLE MODELS

As demonstrated in the previous section, moderate or more severe injuries to the lower extremities among belted drivers in all NASS-CDS frontal crashes occur in relatively small proportions of crashes. An estimated 3.5 percent of drivers experienced lower leg injuries from the floor or foot controls, and an estimated 1.5 percent of drivers experienced upper leg injuries from the instrument panel or knee bolster. In spite of these relatively small proportions, it may still be the case that these injuries are more likely for some crash situations and some occupants than for others. This section explores the relationship between lower and upper injuries, intrusion, and crash severity as measured by delta-V.

Table 9 demonstrates the relationship between intrusion and the estimated percent of drivers with a relevant injury.[8] The estimated percentages in Table 9 indicate that the percent of drivers with a lower leg injury from floor or foot controls generally increases as the maximum intrusion from the floor or toe pan increases. Table 9 also indicates that the estimated percent of drivers with an upper leg injury from the instrument panel or knee bolster is greater when instrument panel intrusion occurs, but the category with the most intrusion (20 to 106 cm) has a lower estimated percent than the other categories with intrusion. The reason appears to be that a case with more than 19 cm of instrument panel intrusion and no injury has a very large sample weight compared to the rest of the cases in the category (36,537 versus a median of 22) even though the category contains 91 observations. That said the differences across the intrusion categories are statically significant at conventional (0.05) levels for both lower and upper leg injuries as indicated by the results of the modified Rao-Scott chi-square test.

[8] The intrusion category of 20 cm to 106 cm is not divided into categories with smaller ranges because of the relatively small sample size.

Table 9: Injuries by Intrusion

Amount of Intrusion	Drivers With Lower Leg Injuries From Floor or Foot Controls By Floor and Toe Pan Intrusion		Drivers With Upper Leg Injuries From Instrument Panel or Knee Bolster By Instrument Panel and Knee Bolster Intrusion	
	Weighted Percent of Drivers With Moderate or More Severe Injuries	Sample Size	Weighted Percent of Drivers With Moderate or More Severe Injuries	Sample Size
None	3.3%	6,802	1.3%	6,969
3 to 9 cm	5.7%	191	20.1%	136
10 to 19 cm	17.3%	154	21.4%	88
20 to 106 cm	23.9%	137	4.3%	91
Any Intrusion	*13.3%*	*482*	*10.0%*	*315*
Total	***3.5%***	***7,284***	***1.5%***	***7,284***

Source: NASS-CDS 1997-2009; weighted total = 2,753,917
Modified Rao-Scott Chi-Squared Test, Pr < 0.01 (lower leg), Pr < 0.01(upper leg)

Intrusion is not the only factor that may be related to the estimated percent of drivers with a relevant injury. One such factor that has a strong relationship with injury is delta-V. Furthermore, since intrusion and crash severity are likely to be related, it is important to consider the independent effect of delta-V. Table 10 demonstrates the relationship between delta-V and the estimated percent of drivers with a relevant injury. The table generally shows that as the change in velocity increases, the estimated percent of drivers with a relevant injury also increases. This finding confirms the importance of delta-V for predicting injuries and the need to control for delta-V when exploring the role of intrusion.

Table 10: Injuries by Change in Velocity

delta-V (kph)	Drivers w/ Lower Leg Injuries From Floor or Foot Controls	Drivers w/ Upper Leg Injuries From Instrument Panel or Knee Bolster	Sample Size
	Weighted Percent of Cases With Moderate or More Severe Injuries	Weighted Percent of Cases With Moderate or More Severe Injuries	
5-19	3.5%	0.6%	2,941
20-29	1.5%	1.0%	2,415
30-39	4.0%	4.5%	1,099
40-49	14.5%	3.0%	443
50-59	20.8%	13.6%	211
60-69	35.0%	23.1%	95
70-129	16.1%	35.1%	80
Total	*3.5%*	*1.5%*	*7,284*

Source: NASS-CDS 1997-2009; weighted total = 2,753,917
Note: Modified Rao-Scott Chi-Squared Test, Pr <0.01 (lower leg), Pr < 0.01(upper leg)

A third table was run to examine whether significant differences existed in the estimated percent of drivers with relevant injuries across the six frontal damage types. The estimates did not indicate any noticeable patterns, and the results of modified chi-squared tests indicated that the differences across the damage types were not statistically significant at the conventional 0.05 level. Therefore, the results are not discussed in the body of this report but are presented in Table 15 in the Appendix.

6. INTRUSION AND INJURY: MULTIVARIATE MODELS

The previous section demonstrated that larger amounts of floor or toe pan intrusion and higher changes in velocity were correlated with higher rates of lower leg injuries in passenger vehicles towed due to damage in frontal crashes. The previous section also demonstrated that the presence of instrument panel intrusion and higher changes in velocity were correlated with higher rates of upper leg injuries. However, there are many other factors that may affect the risk of lower extremity injuries. In additional to testing the hypotheses related to intrusion and delta-V, the statistical models also consider the following hypotheses based upon previous studies:

- *Driver Age:* Older drivers are more likely to experience lower extremity injuries than younger drivers.
- *Driver Gender:* Women are more likely to experience lower extremity injuries than men.
- *Driver BMI:* Drivers with higher BMIs are more likely to experience lower extremity injuries than those with lower BMIs.
- *Vehicle Age:* Newer vehicles (those from model year 2003 and later) are likely to produce different injury patterns than older vehicles (model year 1998 through 2002).
- *Vehicle Type:* Light trucks and vans (LTVs) are likely to produce different injury patterns than passenger cars.

The multivariate statistical method selected for this analysis was logistic regression where the dependent variable was whether a moderate or more severe (AIS 2 or greater) injury occurred (1 = yes, 0 = no). One set of results is presented for floor and toe pan intrusion and lower leg injuries. Another set of results is presented for instrument panel and knee bolster intrusion and upper leg injuries. Two measures of intrusion are considered. One is a continuous variable where no intrusion is recorded as zero and all other intrusions retain their actual values, and the other is an indicator variable where zero represents no intrusion and one represents the presence of intrusion. Finally, all of the logistic models are estimated for all frontal crashes, for the subset of full frontal crashes, and for the subset of left offset and SOI crashes. Table 11 presents the results for lower leg injuries, and the results in Table 12 are for upper leg injuries.

The results for lower leg injuries in Table 11 support most of the hypotheses. Older drivers are more likely to experience lower leg injuries than their younger counterparts in all six versions of the model. Female drivers are more likely to experience lower leg injuries than their male counterparts in five of the six models. BMI has a statistically significant positive effect on the risk of lower leg injuries in the model involving all frontals and full frontals but did not have a statistically significant effect in left offsets and SOIs. Neither the age of the vehicle (newer versus older) nor the body type (LTV versus car) produced a consistent set of results although drivers of newer vehicles appeared less likely to experience injuries than drivers of older vehicles at a statistically significant rate for all frontal crashes.

The results for intrusion and delta-V are more complex. For all frontal crashes, intrusion as a continuous variable has a statistically significant positive effect at the 0.10 level, and intrusion as an indicator variable has a statistically significant positive effect at the 0.05 level. The fact that the effect of intrusion is more statistically significant with an indicator variable than with the continuous variable is not surprising. It is easier for the model to demonstrate, and there is more “confidence” in the result, that any intrusion is more likely to increase the risk of injury versus no intrusion than it is for the model to demonstrate that one additional centimeter of intrusion is more likely to increase the risk of injury. However intrusion is a statistically significant predictor of lower leg injury in both models of full frontal damage and left offset/SOI damage. The model appears to have an easier time identifying the independent effect of intrusion after removing the collisions that occur on the right sides of the vehicles, which are away from the drivers.

Table 11: Logistic Regression Results for the Probability of Driver Having Lower Leg Injury

	Floor/Toe Pan Intrusion in cm (0 for no intrusion)			Floor/Toe Pan Intrusion Indicator (1=yes, 0=no)		
	Estimated Coefficient	**Prob. > Chi-Squared**	**Estimated Odds Ratio**	**Estimated Coefficient**	**Prob. > Chi-Squared**	**Estimated Odds Ratio**
All Frontal Crashes						
Intercept	-10.550	<.0001		-10.567	<.0001	
Intrusion	0.048	0.0823	1.05	**0.701**	0.0386	2.02
Total Delta-V	0.049	0.2135	1.05	0.051	0.1549	1.05
Age	**0.030**	0.0014	1.03	**0.030**	0.0015	1.03
Female (1=yes, 0=no)	**1.962**	<.0001	7.12	**1.942**	<.0001	6.97
BMI	**0.131**	<.0001	1.14	**0.132**	<.0001	1.14
Newer Vehicle (1=yes, 0=no)	**-1.267**	0.0248	0.28	**-1.268**	0.0227	0.28
Light Truck or Van (1=yes, 0=no)	0.151	0.3299	1.16	0.166	0.2890	1.18
Full Frontal Damage						
Intercept	-10.300	<.0001		-10.259	<.0001	
Intrusion	**0.128**	0.0129	1.14	**1.967**	0.0480	7.15
Total Delta-V	-0.026	0.7311	0.98	-0.027	0.7266	0.97
Age	**0.042**	0.0008	1.04	**0.042**	0.0009	1.04
Female (1=yes, 0=no)	**1.535**	0.0183	4.64	**1.536**	0.0174	4.64
BMI	**0.132**	<.0001	1.14	**0.131**	<.0001	1.14
Newer Vehicle (1=yes, 0=no)	-1.039	0.2702	0.35	-1.019	0.2781	0.36
Light Truck or Van (1=yes, 0=no)	-0.016	0.9612	0.98	0.000	0.9988	1.00
Left Offset/SOI Damage						
Intercept	-10.497	<.0001		-9.903	<.0001	
Intrusion	**0.052**	0.0123	1.05	**1.935**	0.0004	6.92
Total delta-V	**0.097**	<.0001	1.10	**0.092**	<.0001	1.10
Age	**0.025**	0.0034	1.03	**0.019**	0.0328	1.02
Female (1=yes, 0=no)	**0.576**	0.0274	1.78	0.356	0.2663	1.43
BMI	0.037	0.2102	1.04	0.033	0.2079	1.03
Newer Vehicle (1=yes, 0=no)	0.182	0.7039	1.20	0.271	0.5504	1.31
Light Truck or Van (1=yes, 0=no)	0.075	0.8392	1.08	-0.022	0.9501	0.98

Source: NASS-CDS 1997-2009, All frontals N = 7,284, Full frontal N=3,078, Left Offset/SOI N=2,076

Note: Coefficients in **bold** are statistically significant at the 0.05 level.

In the models of all frontal crashes and full frontals, the effect of delta-V is not statistically significant at conventional levels. This result requires explanation. Tables 9 and 10 suggest that intrusion and delta-V both predict injuries. It is also is the case that intrusion and delta-V are highly correlated. The weighted average of delta-V when floor or toe pan intrusion occurs is 35 kph versus 21 kph when no intrusion occurs.[9] Therefore, it is likely that the model results are affected by near multicollinearity. In other words, the model has trouble determining the independent effect of delta-V separate from intrusion. Near multicollinearity frequently results in neither variable demonstrating a statistically significant effect because the variables each have very little “independent” effect, but in this instance intrusion (at least in three of the four models) was able to achieve statistical significance at conventional levels. This finding suggests that intrusion is a slightly better predictor of injury than delta-V, but it does not mean that delta-V is unimportant. It only means that in this sample, delta-V did not have enough independent explanatory power left after controlling for intrusion for it to achieve statistical significance.

It may be the case that intrusion had more explanatory power than delta-V because change in velocity is a continuous variable where intrusion was either treated as dichotomous or was nearly dichotomous (since most cases did not have any intrusion). In other words, the rather gross nature of intrusion may make it easier for the variable to predict injury, and thus have more explanatory power, than the finer measure of severity captured by delta-V. However, in the model of left offset/SOI damage, both intrusion and delta-V have the expected statistically significant positive effects on the predicted probability of lower leg injuries.

The results in Table 12 for upper leg injuries provide less consistent support for the hypotheses than the models of lower leg injuries. Older drivers are more likely to experience upper leg injuries than their younger counterparts with full frontal and with left offset/SOI damage, but the estimated effect did not achieve statistical significance in the model of all frontals. BMI has a statistically significant positive effect on the risk of upper leg injuries in the model involving all frontals and full frontal damage but did not have a statistically significant effect in left offset/SOI damage. Female drivers are more likely to experience upper leg injuries than their male counterparts for all frontal crashes, but the result did not hold in the models of full frontal or left offset/SOI damage. Neither the age of the vehicle (newer versus older) nor the body type (LTV versus car) produced a consistent set of results although drivers of newer vehicles appeared less likely to experience injuries than drivers of older vehicles at a statistically significant rate for left offset/SOI damage.

The results for delta-V and intrusion are less complicated for the models of upper leg injuries than those for lower leg injuries. Delta-V has a statistically significant positive effect on the predicted probability of upper leg injury in all six models. Intrusion as a continuous measure does not have a statistically significant effect at conventional levels for all frontal crashes, but the indicator variable for intrusion has a statistically significant positive effect on upper leg injuries. As discussed for lower leg injuries, it is easier for the model to demonstrate that any intrusion is more likely to increase the risk of injury versus no intrusion than it is for the model to demonstrate that one additional centimeter of intrusion is more likely to increase the risk of injury. However, in the models for full frontal and left offset/SOI damage, both continuous intrusion and the presence of intrusion have a statistically significant positive effect on the predicted probability of injury.

Overall, the results from the models of upper leg injuries are not as consistent as the results for lower leg injuries. This result is likely due to the fact that there is less variation for the models of upper leg injuries to explain than in the models of lower leg injuries. Upper leg injuries only affect 1.5 percent of the drivers, while lower leg injuries affect 3.5 percent of drivers.

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[9] The traditional colinearity measure of R-squared is not appropriate in this situation since most of intrusion values are zero.

Table 12: Logistic Regression Results for the Probability of Driver Having Upper Leg Injury

	Instrument Panel Intrusion in cm (0 for no intrusion)			**Instrument Panel Intrusion Indicator (1=yes, 0=no)**		
	Estimated Coefficient	**Prob. > Chi-Squared**	**Estimated Odds Ratio**	**Estimated Coefficient**	**Prob. > Chi-Squared**	**Estimated Odds Ratio**
All Frontal Crashes						
Intercept	-9.2087	<.0001		-9.0773	<.0001	
Intrusion	0.0246	0.1608	1.03	**1.4347**	0.0018	4.20
Total delta-V	**0.0797**	<.0001	1.08	**0.0744**	<.0001	1.08
Age	0.0095	0.3390	1.01	0.0086	0.4088	1.01
Female (1=yes, 0=no)	**0.6512**	0.0362	1.92	0.6313	0.0508	1.88
BMI	**0.0847**	0.0005	1.09	**0.0851**	0.0005	1.09
Newer Vehicle (1=yes, 0=no)	-0.4859	0.2871	0.62	-0.5142	0.2377	0.60
Light Truck or Van (1=yes, 0=no)	-0.0249	0.9572	0.98	-0.0550	0.8997	0.95
Full Frontal Crashes						
Intercept	-11.439	<.0001		-11.141	<.0001	
Intrusion	**0.049**	0.0312	1.05	**2.117**	<.0001	8.31
Total delta-V	**0.065**	<.0001	1.07	**0.056**	<.0001	1.06
Age	**0.022**	0.0059	1.02	**0.019**	0.0187	1.02
Female (1=yes, 0=no)	0.202	0.5623	1.22	0.167	0.6250	1.18
BMI	**0.135**	0.0022	1.15	**0.136**	0.0015	1.15
Newer Vehicle (1=yes, 0=no)	0.276	0.5801	1.32	0.242	0.6349	1.27
Light Truck or Van (1=yes, 0=no)	0.389	0.5407	1.48	0.431	0.4873	1.54
Left Offset/SOI Crashes						
Intercept	-9.020	<.0001		-7.672	<.0001	
Intrusion	**0.041**	0.0129	1.04	**2.851**	<.0001	17.30
Total delta-V	**0.077**	<.0001	1.08	**0.066**	0.0005	1.07
Age	**0.035**	0.0001	1.04	**0.033**	0.0017	1.03
Female (1=yes, 0=no)	0.500	0.2139	1.65	0.238	0.6401	1.27
BMI	0.005	0.9253	1.01	-0.031	0.5199	0.97
Newer Vehicle (1=yes, 0=no)	**-1.704**	0.0013	0.18	**-2.236**	<.0001	0.11
Light Truck or Van (1=yes, 0=no)	1.345	0.0677	3.84	1.420	0.0738	4.14

Source: NASS-CDS 1997-2009, All frontals N = 7,284, Full frontal N=3,078, Left Offset/SOI N=2,076
Note: Coefficients in **bold** are statistically significant at the 0.05 level.

7. DISCUSSION AND CONCLUSIONS

As stated in the introduction, this paper aims to explore the potential causal factors associated with the risk of moderate or more severe lower extremity injuries in frontal crashes with a particular emphasis on the role of intrusion. Establishing these relationships can be difficult for a variety of reasons. One is that the dependent variables of interest have relatively low estimated proportions among belted drivers in model year 1998 vehicles that were towed due to damage in a frontal crash. An estimated 3.5 percent of the drivers examined had a moderate or more severe lower leg injury from the floor or foot controls. An estimated 1.5 percent of the drivers examined had upper leg injuries from the instrument panel or knee bolster. Similarly the main independent variable, intrusion, also has a low estimated frequency of occurrence. An estimated 2 percent of the vehicles examined had floor or toe pan intrusion into the driver's seating position, and an estimated 3 percent had instrument panel intrusion into the driver's seating position. Given that these are small relative frequencies and that NASS-CDS is a statistical sample with significant variation in the sample weights due to unequal probabilities of selection, it can be difficult to establish statistically significant relationships.

Even with these limitations, the overall results appear to support the basic hypothesis that more intrusion is likely to contribute to more leg injuries. Table 9 demonstrates that as the amount of floor and toe pan intrusion increases, the percent of drivers with lower leg injuries from the floor or foot controls also increases. Table 9 also demonstrates that the presence of instrument panel or knee bolster intrusion is associated with a higher percentage of drivers with upper leg injuries, but the relationship between the amount of intrusion and the risk of injury is less clear. At the same time, Table 10 shows that the change in velocity is associated with injury risk and should be considered when assessing the independent effect of intrusion.

The multivariate models used to determine the independent effect of intrusion considered the possible effects of delta-V, age, gender, BMI, vehicle age, and vehicle body type as well as the results presented in other sections of the paper. More specifically, the following hypotheses were considered in the statistical models:

- *Intrusion*: Drivers in vehicles with higher amounts of intrusion are more likely to experience lower extremity injuries than drivers in vehicles with less intrusion.
- *Delta*-V: Drivers in frontal crashes with larger changes in velocity (delta-V) are more likely to experience lower extremity injuries than drivers in frontal crashes with smaller changes in velocity.
- *Driver Age:* Older drivers are more likely to experience lower extremity injuries than younger drivers.
- *Driver Gender:* Women are more likely to experience lower extremity injuries than men.
- *Driver BMI:* Drivers with higher BMIs are more likely to experience lower extremity injuries than those with lower BMIs.
- *Vehicle Age:* Newer vehicles (those from model year 2003 and later) are likely to produce different injury patterns than older vehicles (model year 1998 through 2002).
- *Vehicle Type:* Light trucks and vans are likely to produce different injury patterns than passenger cars.

First, intrusion was examined as a continuous and a dichotomous indicator variable based upon the results in Table 9. Second, separate models were developed for full frontal and left offset/SOI damage to remove crashes that occur on the right side of vehicle. While none of the variables for driver and vehicle characteristics were statistically significant in all twelve models, the results generally supported the hypotheses regarding age, gender and BMI. However, the focus of this analysis is the role of intrusion, and the fact that most of the variables were statistically significant in some of the models suggests that they are important control variables for assessing the independent effect of intrusion.

Overall, the results suggest that intrusion is correlated with lower extremity injuries even when controlling for delta-V. However, the results also indicate that the magnitude of the relationship is conditional on frontal damage type. Table 13 summarizes the results from the 12 logistic models by presenting the odds ratios associated with intrusion from each logistic regression model.

Table 13: Summary of Odds Ratios for Intrusion and Injury

	Drivers With/ Lower Leg Injury		**Drivers With Upper Leg Injury**	
	Odds Ratio for Intrusion in cm	Odds Ratio for Intrusion Indicator	Odds Ratio for Intrusion in cm	Odds Ratio for Intrusion Indicator
All Frontals	Not significant	2.02 (1.04, 3.92)	Not significant	4.20 (1.71, 10.33)
Full Frontal	1.14 (1.03, 1.26)	7.15 (1.02, 50.21)	1.05 (1.00, 1.10)	8.31 (4.05, 17.02)
Left Offset/SOI	1.05 (1.01, 1.10)	6.92 (2.38, 20.16)	1.04 (1.01, 1.08)	17.30 (4.25, 70.47)

Note: 95 percent confidence intervals in parentheses.

The logistic model for all frontals demonstrate that the presence of intrusion has a statistically significant positive effect on the odds ratio for both lower and upper leg injuries, but the continuous measure of the level of intrusion does not have a statistically significant result. As discussed above, it is likely that the model had an easier time determining that any intrusion is more likely to increase the risk of injury versus no intrusion than it is for the model to demonstrate that one additional centimeter of intrusion is more likely to increase the risk of injury.

The results also indicate that intrusion has a greater effect on the odds of injury when the analysis is constrained to full frontal and to left offset/SOI damage. This difference appears to be the result of removing right offset/SOI damage, which are on the far side of the vehicles with respect to the drivers. As seen in Tables 7 and 8, these crashes generally do not have intrusion into the drivers' seating positions, and when intrusion does occur, it tends to be small in magnitude. Therefore, since these crashes have little to no intrusion, removing them from the statistical models reduces some of the background noise that was attenuating the estimated effect of intrusion. The result of removing them is that continuous intrusion is a statistically significant predictor of the risk of injury with full frontal and with left offset/SOI damage, and the estimated odds ratio for the indicator of the presence of intrusion increases in magnitude in full frontal and left side damage types compared to the model of all frontal crashes.

Table 13 also shows that the estimated odds ratios have very large confidence intervals. These large confidence intervals suggest why it is difficult to make statistically significant distinctions across different damage types such as whether the effect of intrusion has a larger magnitude under full frontal crashes than under left offset and SOI crashes. It also suggests that more data is needed to obtain more precise estimates of the effect of intrusion. However, even with these limitations, the overall findings support the hypothesis that intrusion increases the risk of lower extremity injuries.

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Appendix

Table 14: Detailed Lower and Upper Leg Injuries

Injury Severity	Weighted Estimate of Injuries at MAIS for Lower Leg (Sample Size)	Weighted Estimate of Injuries at MAIS and From Floor or Foot Controls (Sample Size)	Weighted Estimate of Drivers With Injury (Sample Size)	Weighted Estimate of Injuries at MAIS for Upper Leg (Sample Size)	Weighted Estimate of Injuries at MAIS and From Instrument Panel of Knee Bolster (Sample Size)	Weighted Estimate of Drivers With Injury (Sample Size)
AIS 2 (Moderate)	132,131 (595)	127,458 (502)	91,625 (303)	35,286 (176)	33,421 (152)	31,031 (132)
AIS 3 (Serious)	12,111 (173)	7,024 (97)	6,015 (88)	17,839 (253)	13,029 (200)	9,785 (145)
AIS 4 (Severe)				172 (4)	135 (3)	135 (3)
AIS 5 (Critical)				5 (1)		
Injury Total	144,243 (768)	134,482 (599)	97,280 (391)	53,301 (434)	46,585 (355)	40,951 (280)
No AIS 2+			2,656,637 (6,893)			2,712,966 (7,004)
Grand Total			*2,753,917 (7,284)*			*2,753,917 (7,284)*

Source: NASS-CDS 1997-2009

Table 15: Injuries by Frontal Damage Type

Frontal Damage Type	Drivers With Lower Leg Injuries From Floor or Foot Controls	Drivers With Upper Leg Injuries From Instrument Panel or Knee Bolster	Sample Size
	Weighted Percent of Cases With Moderate or More Severe Injuries	Weighted Percent of Cases With Moderate or More Severe Injuries	
Center	6.0%	7.0%	358
Full Frontal	5.9%	1.3%	3,078
Left Offset	0.8%	1.1%	1,325
Left SOI	0.8%	1.0%	751
Right Offset/SOI[10]	2.6%	1.6%	1,772
Total	*3.5%*	*1.5%*	*7,284*

Source: NASS-CDS 1997-2009; weighted total = 2,753,917
Note: Modified Rao-Scott Chi-Squared Test, Pr >0.05 (lower leg), Pr >0.05 (upper leg)

[10] Right offset and SOI combined due to the small number of cases of intrusion in each category.

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