UPDATED ANALYSIS OF LOWER EXTREMITY INJURY RISK IN FRONTAL CRASHES IN THE UNITED STATES

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ABSTRACT

Injuries to the lower extremities continue to occur in frontal crashes despite increased attention on vehicle structure and restraint design. Since lower extremity injuries can lead to costly rehabilitation and long-term disability, it is important to understand their causation and how well modern design practices are affecting their incidence and severity. This study investigates lower limb injury risk and causation in a U.S. crash database, and compares the risk and severity based on the nature of the crash and vehicle specifications. This study uses weighted NASS-CDS data to give an overall view of lower limb injury risk over a period from 1994 until 2007. Crashes will be categorized by intrusion level, delta-V, and vehicle model year. Particular interest will be paid to leg, foot and ankle injuries as well as occupant factors and intrusion levels.

A review of the representative data suggests that foot and ankle injury prevalence has not decreased in newer model-year vehicles, and that injury risk to the foot and ankle has actually increased despite structural improvements aimed at reducing footwell deformation. When broken down by delta-V, the trends vary, but the majority of the injuries occur at lower crash severities. Although vehicle structures and restraints have been optimized for improved performance in consumer information and regulatory tests, the risk of sustaining lower extremity injuries, especially to the foot and ankle, remains an issue that deserves further attention.

INTRODUCTION

Improvements to restraint system performance in the 1980s and 1990s precipitated an increase in attention paid to lower extremity injuries sustained in frontal crashes. A number of publications highlighted the importance of the lower extremities in terms of the overall injury distribution – with the lower extremities accounting for a large portion of the frontal crash injuries sustained [States, 1986; Pattimore *et al.*, 1991; Morgan *et al.*, 1991; Dischinger *et al.*, 1994, Pilkey *et al.*, 1994]. Though rarely life-threatening, lower extremity injuries can lead to long-lasting disability with physical and psychosocial effects [Read *et al.*, 2004]. Despite extensive study, the factors related to foot and ankle injury causation remain unclear, though some studies have postulated that toepan intrusion and pedal interaction were responsible for many of the injuries.

An in-depth analysis of crashes from the U.K. indicated that the majority of the ankle injuries were caused by intrusion of the toepan [Manning *et al.*, 1998]. Thomas *et al.* [1995] also concluded that toepan intrusion increased the risk of sustaining lower limb injuries. Conversely, an investigation of field crashes spanning the period from 1988 to 1995 in the U.S. suggested that almost all lower limb injuries occurred in frontal crashes with delta-V below 50 km/h and with toepan intrusion levels below 3 cm [Crandall *et al.* 1995; Crandall *et al.*, 1998]. Crandall *et al.* [1998] cautioned that the effects of footwell intrusion may not be fully captured by a static post-crash measurement.

Occupant anthropometry has also been shown to affect lower extremity injury risk. Crandall *et al.* [1996] concluded that foot and ankle injury risk decreased with increasing driver height. That same study also indicated a higher risk for females than for males. Differences in seating positions associated with different heights, in addition to greater injury tolerance for larger occupants, likely play a role in this outcome. Differences in seating positions associated with different vehicle types are also likely to affect lower extremity injury distribution and risk [Rudd *et al.* 2006].

The objective of this study was to take an updated look at the nature of lower extremity injuries in frontal crashes. The Insurance Institute for Highway Safety (IIHS) included measurements of toepan intrusion in its frontal offset rating program, and the result was that many newer vehicle designs experience less toepan deformation in offset frontal crashes than earlier models. One of the primary interests was how modern vehicle designs have affected the lower extremity outcome in frontal crashes. Other issues of interest included vehicle type, occupant height, and crash severity.

METHODS

Case data were selected from the National Automotive Sampling System/Crashworthiness Data System (NASS/CDS) for analysis in this study (case years 1994 through 2007). Model year 1995 and newer light vehicles involved in tow-away frontal crashes without rollover were included. Adult occupants (thirteen years of age or older) seated in an outboard first row position (seatpos 11 or 13) with an available frontal air bag were applicable for analysis if they were properly belted and not ejected from the vehicle. Since knowledge of injuries was critical to this analysis, only those cases with known injury information were included.

The crashes were classified as full frontal, left offset, or right offset based on the criteria specified by Stucki *et al.* [1998]. The vehicle's general area of damage (GAD1), principal direction of force (DOF1), object contacted and damage location were used to determine the crash mode. Vehicles involved in rollover crashes were not considered. All data presented have been weighted according to NASS/CDS recommendations except where noted.

The representative CDS data were analyzed using SAS 9.1 software (SAS Institute Inc., Cary, NC) and standard errors from the sampling procedures were accounted for using the PROC SURVEY functions with the stratification information. Risks were calculated by dividing weighted incidence by weighted exposure. Odds ratios and confidence intervals were calculated using SURVEYLOGISTIC.

This study focused on injuries to the lower extremities, which were broken down into the following sub-regions: pelvis, hip, thigh, knee, leg, and foot/ankle. The injuries were divided into the specific sub-regions based on their AIS code, and the breakdown follows clinical definitions for the lower extremity regions [Kuppa *et al.*, 2003]. Knee sprains were not considered to be AIS 2 injuries for this analysis. In the second half of the analysis, special emphasis was placed on the leg, foot and ankle, where ankle injuries include malleolar fractures.

RESULTS

There were 15,364 occupants in the selection of CDS cases meeting the frontal crash and occupant criteria, which represented 6,423,619 total occupants after weighting. Of the frontal crash occupants selected, 1,370 sustained at least one AIS 2+ lower extremity injury, which became 151,362 occupants after weighting. Summary statistics for the occupants and crashes are shown in Table 1. The age distribution for the occupants is shown in Figure 1 and the height breakdown by gender is shown in Figure 2. A distribution of total delta-V is provided in Figure 3 sorted by the crash type. A large majority of the crashes had a delta-V of less than 30 km/h.

Table 1.
Summary statistics for CDS dataset

	Group	Mean	Percentage
Age		36.3 years	
	Male	37.5 years	49.4%
	Female	38.2 years	50.6%
Height		171.0 cm	
	Male	178.0 cm	
	Female	164.1 cm	
Delta-V		20.0 km/h	
Crash Type			
	Full Frontal		20.9%
	Left Offset		41.2%
	Right Offset		37.7%
Seating Position			
	Driver		82.5%
	Right Front Passenger		17.5%

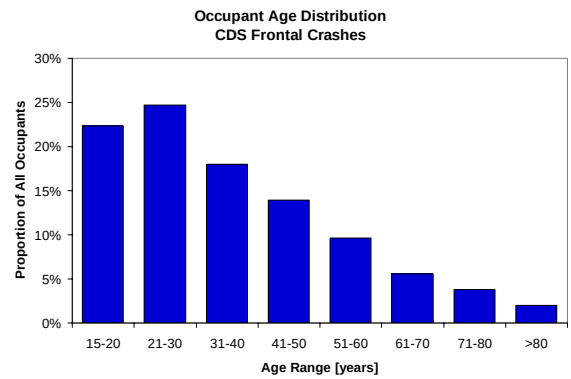

Figure 1. Occupant age distribution (weighted) in CDS frontal cases, all occupants.

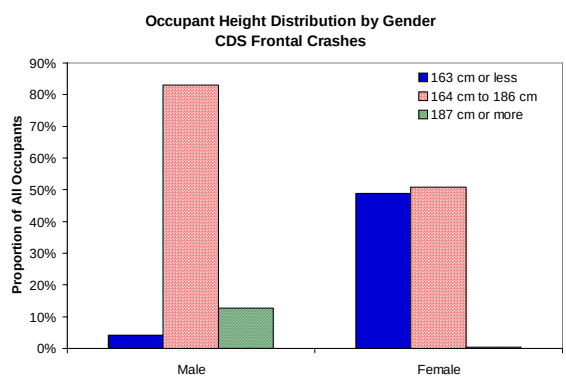

Figure 2. Occupant height distribution by gender (weighted) in CDS frontal cases, all occupants.

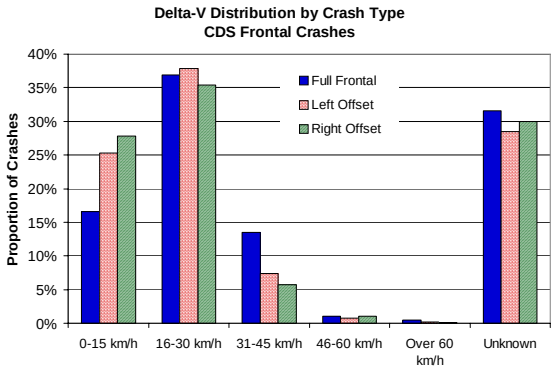

Figure 3. Crash delta-V distribution (weighted) in CDS frontal cases by crash type.

The distribution of all AIS 2+ lower extremity injuries by sub-region was determined as a function of some vehicle and occupant factors. A comparison by vehicle model year, where 1995-2000 model years were considered the older group and 2001+ were considered the newer group, is shown in Figure 4. The proportion of knee and foot/ankle injuries is higher in the newer group, while the other sub-regions constituted fewer of the lower extremity injuries. Hip injuries made up a similar proportion for both groups.

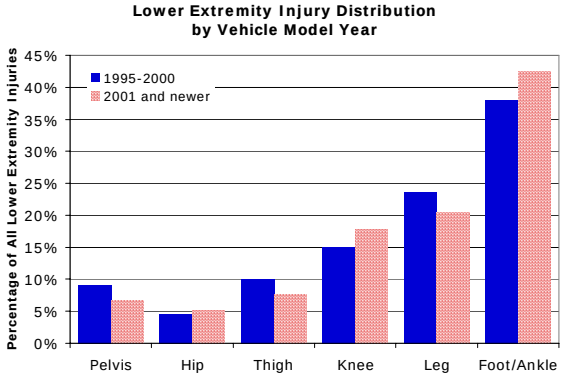

Figure 4. Distribution of body regions sustaining at least AIS 2+ injury in CDS frontal crashes by vehicle model year.

Vehicles were also classified by type, where pickups, sport utility vehicles, and vans were lumped together in the LTV group. The injury distribution comparison for passenger cars compared to LTVs is shown in Figure 5. The proportion of below-knee injuries is somewhat lower for LTV occupants, but LTV occupants tended to have more above-knee injuries overall compared to car occupants.

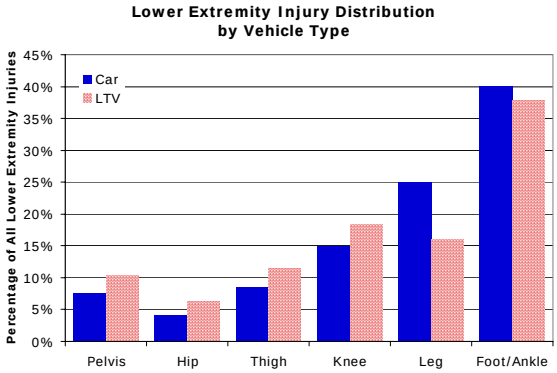

Figure 5. Distribution of body regions sustaining at least AIS 2+ injury in CDS frontal crashes by vehicle type.

Prior studies have indicated a gender bias with respect to lower extremity injuries, so the distribution among males and females was calculated and is shown in Figure 6. Men suffered a greater proportion of pelvis and thigh injuries, but the female group sustained a larger number of foot and ankle injuries.

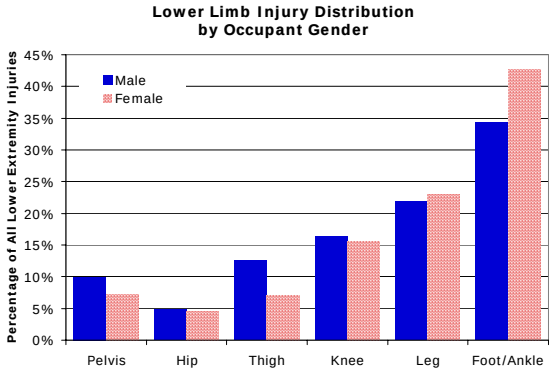

Figure 6. Distribution of body regions sustaining at least AIS 2+ injury in CDS frontal crashes by occupant gender.

Prior studies have also indicated differences in lower extremity injuries based on occupant anthropometry. The injured occupants were segregated by height into three groups, one for those 163 cm (5'4") or shorter, one for those between 164 cm and 186 cm (5'5" to 6'1"), and a third for those taller than 187 cm (6'2"). The distribution based on height is shown in Figure 7. The most prevalent trends are for an increase in above-knee injuries and a decrease in foot/ankle injuries with increased occupant height.

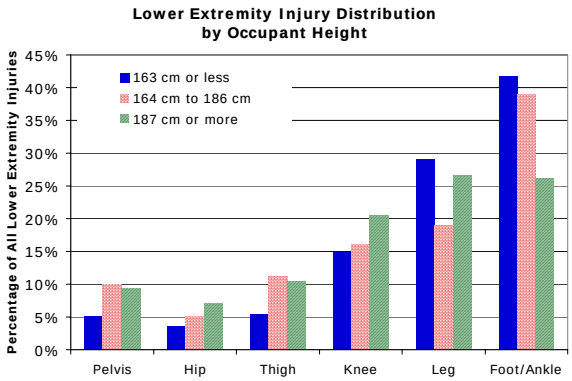

Figure 7. Distribution of body regions sustaining at least AIS 2+ injury in CDS frontal crashes by occupant height.

AIS 2+ injury risk was calculated for the lower extremity sub-regions based on the vehicle and occupant factors compared in Figures 4 through 7. Odds ratios were calculated between groups, and are shown below the risk values in Table 2. Statistical significance of each comparison, based on α=0.05, is indicated by an asterisk next to the odds ratio. A comparison of risk values for drivers based on the crash type has also been included.

Further analysis was conducted looking only at injuries to the leg and foot/ankle complex. Injury incidence and risk were calculated based on the effects of toepan intrusion, delta-V, gender/height and vehicle type/height. Each of the accompanying charts shows the distribution of frontal crashes for three sets of conditions: the left column (dark blue) shows the distribution for all frontal crashes, the middle column (speckled red) shows the distribution among crashes in which an AIS 2+ leg injury was sustained, and the right column (green stripes) shows the distribution among crashes in which an AIS 2+ foot or ankle injury was sustained. All columns of each color add up to 100 percent. Following each chart, a table lists the calculated leg and foot/ankle AIS 2+ injury risk values for the various levels of vehicle and occupant effects.

Figure 8 shows the effects of toepan intrusion. Most frontal crashes (96%) occur with little or no toepan intrusion, and nearly 70% of the leg and foot/ankle injury crashes also occur with little or no toepan intrusion. Injury risk generally increases with higher levels of toepan intrusion (Table 3). The foot/ankle complex is generally at a higher risk than the leg, regardless of intrusion level.

Table 2
Injury risk (AIS 2+) and odds ratios for lower extremity sub-regions based for various vehicle and occupant factors

	Pelvis	Hip	Thigh	Knee	Leg	Foot/Ankle
Model Year						
Old (1995-2000)	0.27%	0.14%	0.30%	0.45%	0.71%	1.15%
New (2001+)	0.23%	0.17%	0.26%	0.60%	0.69%	1.44%
New vs. Old	*0.83*	*1.26*	*0.86*	*1.33*	*0.97*	*1.26*
Vehicle						
Car	0.25%	0.14%	0.28%	0.50%	0.84%	1.34%
LTV	0.27%	0.17%	0.30%	0.49%	0.42%	1.00%
LTV vs. Car	*1.08*	*1.19*	*1.06*	*0.98*	*0.50*	*0.74*
Gender						
Male	0.25%	0.12%	0.32%	0.41%	0.55%	0.86%
Female	0.27%	0.17%	0.26%	0.58%	0.86%	1.59%
Female vs. Male	*1.08*	*1.38*	*0.83*	*1.41*	*1.57**	*1.86*
Height						
Short (≤163 cm)	0.19%	0.14%	0.20%	0.56%	1.10%	1.58%
Average (164 -186 cm)	0.29%	0.15%	0.33%	0.48%	0.57%	1.16%
Tall (≥187 cm)	0.18%	0.14%	0.21%	0.40%	0.53%	0.52%
Short vs. Average	*0.65**	*0.91*	*0.62*	*1.17*	*1.96**	*1.36*
Tall vs. Average	*0.62*	*0.91*	*0.62*	*0.84*	*0.93*	*0.44**
Crash Type (Drivers only)						
Full Frontal	0.50%	0.14%	0.37%	0.63%	0.65%	2.12%
Left Offset	0.28%	0.19%	0.29%	0.48%	0.78%	1.26%
Right Offset	0.20%	0.14%	0.27%	0.52%	0.42%	1.06%
Left vs. Full	*0.56**	*1.39*	*0.79*	*0.77*	*1.19*	*0.59*
Right vs. Full	*0.40**	*1.07*	*0.74*	*0.83*	*0.64*	*0.50*

Note: Comparisons between groups (odds ratios) are shown in *italicized text*. An asterisk (*) indicates statistical significance for the differences in injury risk for the comparison groups.

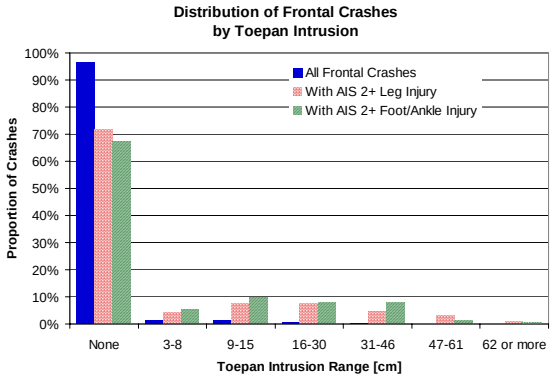

Figure 8. Distribution of crashes by toepan intrusion level for all frontal crashes, those in which the occupant sustained at least one AIS 2+ leg injury, and AIS 2+ foot/ankle injury.

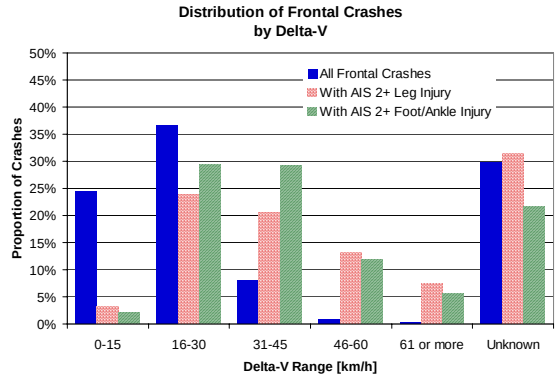

Figure 9. Distribution of crashes by delta-V for all frontal crashes, those in which the occupant sustained at least one AIS 2+ leg injury, and AIS 2+ foot/ankle injury.

Table 3.
AIS 2+ injury risk based on recorded toepan intrusion level

Toepan Intrusion Level	Leg Injury Risk	Foot/Ankle Injury Risk
None	0.52%	0.86%
3-8 cm	2.25%	4.59%
9-15 cm	4.56%	10.3%
16-30 cm	8.99%	16.0%
31-46 cm	14.6%	42.9%
47-61 cm	56.4%	39.9%
62+ cm	44.8%	50.8%

The majority of all frontal crashes occur with a delta-V of less than 30 km/h (Figure 9). When considering those with leg or foot/ankle injuries, the largest subset is the 16-30 km/h group and almost none occur in the lowest severity group. Similar to the trend seen for toepan intrusion, greater severity as indicated by a higher delta-V generally results in a higher injury risk (Table 4). One important consideration to make here is the inherent limitations in the calculation of delta-V. Crashes with other than full overlap may result in an underestimated delta-V.

Occupants were broken down by their gender and height, and the distribution of crashes is shown in Figure 10. The blue columns give an indication of the overall gender and height breakdown for frontal crash exposure. Of the occupants 163 cm or shorter, females dominated the overall number exposed, but had a disproportionately high number of leg and foot/ankle injuries. In the middle height range, females tended to have more foot/ankle injuries than

Table 4.
AIS 2+ injury risk based on delta-V

Delta-V Range	Leg Injury Risk	Foot/Ankle Injury Risk
0-15 km/h	0.10%	0.10%
16-30 km/h	0.46%	0.99%
31-45 km/h	1.80%	4.51%
46-60 km/h	10.5%	16.5%
61+ km/h	23.2%	29.9%
Unknown	0.75%	0.90%

males. The risk values for the various height and gender groups are shown in Table 5. Odds ratios for females compared to males have also been included in this table for the three height groups. Statistical significance at the α=0.05 level was denoted by an asterisk next to the odds ratio. Women have a significantly higher risk of foot/ankle injuries compared to men for the short and middle height groups. Leg injury risk is significantly higher for women compared to men 163 cm or less.

Occupants were also broken down by height based on the type of vehicle. Figure 11 shows the distribution for cars and LTVs and risk values are tabulated in Table 6. Short car occupants sustain a disproportionately high number of leg and foot/ankle fractures, and their risk is higher than in LTVs though only significant at the 0.05 level for the leg. Car occupants below 186 cm in height generally had a higher risk of leg and foot/ankle injury, but the tallest occupant group showed higher risk in LTVs. Tall occupants were nearly twice as likely to sustain a foot/ankle injury in an LTV compared to a car.

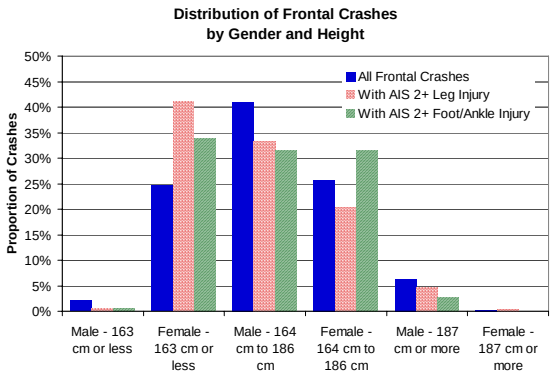

Figure 10. Distribution of crashes by occupant gender and height for all frontal crashes, those in which the occupant sustained at least one AIS 2+ leg injury, and AIS 2+ foot/ankle injury.

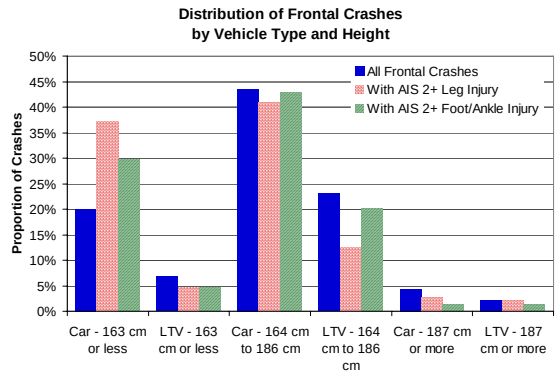

Figure 11. Distribution of crashes by vehicle type and occupant height for all frontal crashes, those in which the occupant sustained at least one AIS 2+ leg injury, and AIS 2+ foot/ankle injury.

Table 5.
AIS 2+ injury risk and odds ratios based on occupant gender and height

Gender	Height	Leg Injury Risk	Foot/Ankle Injury Risk
Male	≤163 cm	0.22%	0.27%
	164-186 cm	0.57%	0.95%
	≥187 cm	0.51%	0.53%
Female	≤163 cm	1.18%	1.69%
	164-186 cm	0.56%	1.51%
	≥187 cm	1.14%	0.17%
Female vs. Male	*≤163 cm*	*5.39**	*6.38**
	164-186 cm	*0.97*	*1.60*
	≥187 cm	*2.27*	*0.33*

Note: Comparisons between genders (odds ratios) are shown in *italicized text*. An asterisk (*) indicates statistical significance for the differences in injury risk for the comparison groups.

Table 6.
AIS 2+ injury risk and odds ratios based on vehicle type and occupant height

Vehicle	Height	Leg Injury Risk	Foot/Ankle Injury Risk
Car	≤163 cm	1.31%	1.83%
	164-186 cm	0.66%	1.21%
	≥187 cm	0.45%	0.40%
LTV	≤163 cm	0.48%	0.83%
	164-186 cm	0.38%	1.08%
	≥187 cm	0.68%	0.74%
LTV vs. Car	*≤163 cm*	*0.36**	*0.45*
	164-186 cm	*0.58*	*0.89*
	≥187 cm	*1.51*	*1.86*

Note: Comparisons between vehicle types (odds ratios) are shown in *italicized text*. An asterisk (*) indicates statistical significance for the differences in injury risk for the comparison groups.

DISCUSSION

The CDS dataset contained mostly drivers, and the distribution by gender was close to even. About two-thirds of the occupants were 40 years of age or younger. Most of the males were in the middle height group (164 cm to 186 cm), and the females were fairly evenly divided between the lowest and middle height group. Of the crashes with a known delta-V, over 85% were at a delta-V of 30 km/h or less. Based on this distribution, even with a higher injury risk in higher severity crashes, it makes sense that a large portion of the lower extremity injuries will occur with a delta-V below 50 km/h as claimed by Crandall et al. [1998]. The greatest potential for exposure, even though injury risk is lower, is generally in crashes less severe than the NCAP and IIHS tests.

One of the primary objectives of this study was to compare lower extremity injury prevalence in frontal crashes of newer vehicles to that in older vehicles. The distribution of injuries to the lower extremities was found to be slightly different for the newer group compared to the older group. There was a tendency for occupants of newer vehicles to suffer more foot/ankle and knee injuries and less pelvis, thigh and leg injuries. Foot/ankle injury risk was higher for the newer vehicles as indicated by the odds ratio of 1.26, though this was not significant at the 0.05 level (confidence interval 0.65, 2.42). One key factor related to the model year analysis was the cutoff year for the newer versus older vehicles. An analysis of IIHS results indicated that more than two-thirds of

the 2001 model year vehicles received Good or Acceptable scores in the frontal offset crashworthiness evaluation. The proportion of Good or Acceptable vehicles continued to increase thereafter, so this was chosen as a cutoff based on the assumption that a sizeable number of the vehicles would have better structural frontal crash performance. With this breakdown, approximately 29% of the total number of weighted cases was in newer vehicles. It was felt that this cutoff ensured the new group contained enough crashes for a comparison yet reflected more modern vehicle designs. One limitation in this approach comes from the staggering of vehicle redesign cycles, which means that some 2001 and newer vehicles are older designs that may not reflect newer design practices.

The overall distribution of injuries did not vary much in passenger cars compared to LTVs, though LTVs did seem to have a larger proportion of above-knee injuries. To offset this difference, LTV occupants appeared to have a smaller proportion of leg injuries compared to car occupants. In terms of AIS 2+ injury risk, there were no significant differences between the two vehicle types, but below-knee risk was generally lower in the LTVs. With vehicle interior geometry varying so widely among LTVs, and even among passenger cars, any effects of differences in seating position on injury risk are probably not evident with such an analysis. A more appropriate, and telling, characterization would have to take actual geometry into account.

The role of gender on injury distribution and risk was similar to that found in previous studies. Males tended to sustain a greater relative number of pelvis and thigh injuries while women suffered a notably greater proportion of foot/ankle injuries. Females were 1.86 times more likely to sustain an AIS 2+ foot/ankle injury than men, a difference that was nearly significant if α=0.10. Women were found to be 1.57 times more likely to sustain leg injuries. Prior studies have postulated that both geometric and footwear differences may explain the higher risk for women [Crandall et al., 1996]. An analysis of footwear was not performed in this study, but the height analysis offers some additional insight.

Shorter occupants sustained more foot/ankle injuries than their taller counterparts, based on the overall injury distribution. The shortest occupants tended to sustain fewer above-knee injuries relative to taller occupants, but the middle and tall height groups were more similar to one another. Looking at the calculated risk values suggests that shorter occupants tend to fare worse for injuries to the lower regions (knee, leg, foot/ankle). Those 163 cm in height or less are nearly twice as likely as middle-height occupants to sustain an AIS 2+ leg injury. The shortest occupants were significantly less likely to sustain a pelvic fracture. Crandall et al. [1996] suggested that the smaller drivers' higher injury risk may be associated with differences in the gap between the heel and the floor during pedal application. It is likely that the gap arises from both shorter foot length and overall geometry factors that result from shorter leg and thigh length within a vehicle geometry that is not as accommodating for shorter occupants. Pedals that adjust in both longitudinal and vertical directions may help to eliminate the heel gap among shorter drivers during braking maneuvers.

The crash type analysis in Table 2 shows that full frontal-type crashes generally resulted in a higher lower extremity injury risk compared to left- or right-offset crashes. The highest risk value was for foot/ankle injuries in full frontal crashes, which was close to being significantly higher than that in both the left- and right-offset modes. Injuries to the leg were more likely to occur in left-offset crashes compared to full frontals, but the difference was not significant. Since greater toepan intrusion is typically expected in an offset crash compared to a frontal, this result suggests that toepan intrusion may not be driving factor for foot/ankle injuries since the full-frontal mode had the highest risk.

Additional analysis was conducted with a special emphasis on below-knee injuries. Since toepan intrusion has been debated as a cause of increased lower extremity injury risk, the distribution of crashes was calculated based on the level of toepan intrusion for all crashes and for those with below-knee injuries. Overall, as shown in Figure 8, most crashes occur with little or no toepan intrusion – even those with AIS 2+ injuries to the leg, foot and ankle. As expected, injury risk increases with greater toepan intrusion, but with about 70% of the tibia and foot/ankle injuries occurring with less than 3 cm of intrusion, it appears that despite a higher risk, intrusion is not necessary to produce AIS 2+ injuries. Based on the exposure numbers alone, it is evident that efforts to reduce toepan intrusion may not completely address the problem.

Almost no leg or foot/ankle injuries occur in the crashes with delta-V below 15 km/h, though the majority occur in crashes with a delta-V below 45 km/h, considering only those crashes with known delta-V. As with toepan intrusion, injury risk does consistently increase with higher crash severity as

measured by delta-V. Even though the calculated foot/ankle injury risk is below 5 percent for crashes with delta-V 45 km/h or less, sizeable reductions in injury prevalence could be achieved by addressing moderate severity crashes based simply on exposure. Findings related to the delta-V must be viewed as generalizations due to the inherent limitations in the calculation of delta-V in anything other than a full frontal crash.

Taking another, more detailed, look at the effects of occupant height and gender in Figure 10 and Table 5, it becomes evident that the effect of gender may be related to more than just typical height differences between men and women. Relatively few males were in the shortest height group, but they demonstrated about one-sixth the foot/ankle injury risk of the female occupants of similar height – and the result was significant. In the middle height group, the female occupants had a higher risk of foot/ankle injury compared to the males. Females in the shortest subset were five times more likely than males to sustain an AIS 2+ leg injury. While the proportion of males in the shortest subset was small compared to the females (about 7% of total weighted cases), the differences in foot/ankle injury risk for all occupants shorter than 186 cm does suggest that height alone does not explain the difference between genders. The difference could be due to a lower injury tolerance among the female population or because of differences in foot size despite equivalent height. If women generally have smaller feet, the heel gap issue proposed by Crandall et al. [1996] may affect women more so than men.

The vehicle type analysis was conducted again, but with further breakdown of the cases by occupant height as shown in Figure 11 and Table 6. In this dataset, car occupants outnumbered LTV occupants by a factor of about 2 based on weighted counts. Among the shortest occupants, those occupying cars were injured more frequently than those in LTVs. While not statistically significant at the α=0.05 level, the foot/ankle risk in LTVs was 0.45 of that in cars for this group (confidence interval 0.2, 1.01). The leg injury risk for LTV occupants compared to car occupants for this height group was significant at 0.36. It is possible that the generally higher seating position in LTVs compared to cars offers some benefit to occupants 163 cm or shorter in height, though a more detailed geometric analysis would need to be performed given the vast range of seating positions available in both vehicle classes. Among middle height occupants, the foot/ankle risk in cars and LTVs was similar. Tall occupants in LTVs were more likely to suffer a foot/ankle or leg injury than those riding in cars. While it is unlikely that the tallest occupants develop a gap between their heel and the floor, overall lower limb positioning associated with the higher seating position may predispose their lower extremity, especially the foot and ankle, to more injurious loading conditions. This finding does not follow the general trend for taller occupants to have lower injury risk, so further investigation of the seating position and vehicle interior geometry effects should be conducted.

CONCLUSION

This study presented updated lower extremity injury trends based on vehicle and occupant factors in order to show where improvements can be made in frontal crash safety given that the prevalence of lower limb injuries has remained high. Since the IIHS frontal offset test has placed an emphasis on reduced toepan intrusion, it was desired to evaluate any lower limb injury trends in newer model vehicles. The analyses conducted yielded the following conclusions about lower extremity injuries in frontal crashes:

- The risk of AIS 2+ foot/ankle injury is slightly higher for occupants of MY 2001 and newer vehicles
- Females are more likely to sustain leg and foot/ankle injuries than males
- Occupants less than 164 cm in height are twice as likely to sustain leg injuries than those 164 cm to 186 cm in height
- Although the injury risk is about 1%, most foot/ankle injuries occur with less than 3 cm of toepan intrusion
- Female occupants less than 164 cm in height are at significantly higher risk of foot/ankle and leg injuries than males in the same height range
- Tall occupants of LTVs show higher risk of below-knee injury compared to those in cars
- Full frontal crashes have a higher risk of foot/ankle injuries compared to offset frontal crashes

Understanding the kinematics and dynamics of the lower extremities under different loading conditions and with different occupant configurations is not possible based on field data alone. Further explanation of these findings may be possible with computational modeling or with physical tests. Such an effort is critical for minimizing real-world foot/ankle injury risk, as the general trend with newer vehicles has not shown a reduction from the efforts to reduce toepan intrusion.

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