Injury Risk in Frontal Crashes with Guardrail and Guardrail End Terminals

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By

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Frontal impacts, due to their prevalence, account for about 77% of all injuries and 62% of all fatalities in guardrail crashes. This analysis examined the distribution of injury in frontal guardrail crashes using 711 crash records extracted from the National Automotive Sampling System – Crashworthiness Data System, spanning the years from 1997 to 2008. Frontal crashes to end terminals were found to carry injury odds 5.1 times greater than frontal crashes to the guardrail face. End terminals compliant with NCHRP Report 350 safety criteria have injury odds between 11 and 19 times lower than non-compliant designs. Rollover and unbelted occupants were associated with 25% of all frontal guardrail crashes, yet were present in 61% of serious injury crashes. Rollover occurred in 9.2% of all frontal guardrail crashes and was initiated by the guardrail in roughly 49% of instances. Guardrail end terminal contact increased rollover odds by 6.7 times over contact with the guardrail face.
INTRODUCTION

According to the National Automotive Sampling System – Crashworthiness Data System (NASS-CDS), each year in the United States from 1997 to 2008 there were on average about 50,000 police-reported tow-away crashes of passenger vehicles where the most severe impact was with guardrail. This is about 8% of all single-vehicle crashes (on the basis of most severe impact) in an average year. These crashes involved an average of 64,000 individual occupants yearly. About 3 out of every 4 such crashes were frontal impacts; although side crashes with guardrail carry a higher inherent risk of injury and fatality, the frontal crash mode, due to its prevalence, accounted for about 75% of all of guardrail injuries and 60% of fatalities. In raw numbers, this corresponds to approximately 1,030 serious injuries and 245 fatalities (conservatively) in an average year.

Bryden and Fortuniewicz (1) examined the effects of vehicle, barrier type and other highway features on guardrail crash severity using New York state data from 1982-1983. Fatalities were less frequent in crashes with roadside barriers than with all roadside objects taken together. Amongst roadside barriers, fatalities were less common when the impact was within the design envelope of the barrier and when the barrier was a “current” system at the time of the study. About 58% of designed-for barrier impacts resulted in some level of injury or fatality. Twenty-six percent of barrier crashes had a secondary event (including rollover), and this 26% of crashes accounted for nearly 90% of fatalities and half of A-level injuries. Light trucks, vans and SUVs (LTVs) were observed to have higher injury rates in roadside crashes than cars.

Hunter, Stewart and Council (2) extensively studied differences in injury rates between different guardrail and end terminal types, between vehicle types and between length-of-need and end terminals. They used the Longitudinal Barrier Special Study (LBSS) file, a highly detailed set of about 1200 longitudinal barrier crashes collected from 1982 to 1986 as part of the NHTSA’s NASS activities. Briefly, their main findings were that weak post guardrail carried less risk of injury than other types; that blunt and turn-down end terminals carried greater risk of serious injury than length-of-need; and that end terminal impacts were more likely to produce injury than length-of-need impacts because of higher inherent injury risk as well as a greater association with rollovers.

Viner, Council and Stewart (3) examined injury outcomes by vehicle type in roadside safety appurtenance crashes from 1985-1990, using Michigan and North Carolina state data. They found that, for cars, serious injury occurred in 19% of reported guardrail end crashes and 6% of guardrail face crashes while for pickup trucks, the respective percentages were 13% and 8%. They also found that pickup trucks were three times more likely to roll over than cars when striking a guardrail face but that, in rollovers, pickup trucks had less than half the serious injury rate of cars. They concluded that the higher serious injury rate for pickup trucks in guardrail face crashes was due to the higher rollover rate and decreased belt use relative to cars.

Bligh and Mak (4) examined the crashworthiness of different roadside hardware including guardrail using nationally representative data from 1987-1995. Based on NASS General Estimates System (NASS-GES) data, crashes with guardrail resulted in some level of injury for 31.5% of passenger cars and 39.1% of LTVs and in serious injury or fatality (A or K) for 5.3% of cars and 11.4% of LTVs. LTVs rolled over in 11.2% of guardrail crashes while cars rolled over in 4.7% of guardrail crashes.

NCHRP Report 490 (5) developed recommendations for standardizing in-service evaluations of roadside safety hardware. Pilot in-service analyses using these recommendations were conducted for hardware including guardrail and several end terminal systems from 1997-1999. The report also included a comprehensive literature review of roadside safety hardware evaluations up to 2003. Out of 115 reported crashes with Breakaway Cable Terminals (BCTs) or Modified Eccentric Loader Terminals (MELTs), 60% resulted in property damage only and only 5 involved serious or fatal (A or K) injury. Seventy-five percent of the 400 police-reported guardrail crashes in the sample were property-damage-only; 13 involved A or K outcomes. Injury was found to be less common with G1 guardrail than with G4 guardrail, and guardrail damage was less severe with G1 than with G4 guardrail.
The majority of the literature concerning injury risk in guardrail crashes uses data from the first half of the 1990s, or earlier. Substantial changes to the U.S. vehicle fleet have happened in the intervening 20 years: airbags became mandatory on new vehicles only in 1997-1998 and even then many older vehicles were still in the fleet; seatbelt use rates have risen since the early 1990s; crashworthiness of the average fleet vehicle has improved drastically thanks to stringent Insurance Institute for Highway Safety (IIHS) and NHTSA crash testing standards. Roads and roadside hardware have changed as well. In 1995, the national maximum speed limit law was repealed and in late 1998, NCHRP Report 350 (6) was adopted by the FHWA as the standard for roadside safety appurtenances on the National Highway System. In light of these changes, studies based on data from the 1990s or earlier cannot safely be assumed to represent injury risks posed to the current vehicle fleet.

OBJECTIVE

The goal of this study was to determine the injury risks of frontal crashes with guardrail using data representative of the current vehicle fleet and roadside hardware. Particular subjects of interest included the risk of guardrail end terminal impacts relative to the guardrail face, the influence of vehicle type and the effect of compliance with NCHRP 350 safety criteria.

METHODS

Data for this analysis were obtained from the NASS-CDS. The NASS-CDS is a nationally representative database of police-reported tow-away crashes maintained by the US Department of Transportation. NASS-CDS cases are investigated by trained crash investigators and contain information well beyond that found in police accident reports. Cases were selected based on the following criteria:

- Sample year between 1997 and 2008 (inclusive);
- The vehicle was physically inspected by the case investigator;
- The highest-severity impact in the crash was either an impact with guardrail or a rollover which was initiated by an impact with guardrail;
- The damage plane corresponding to the highest-severity impact (or guardrail impact which initiated rollover) was coded by the investigator as ‘Front’.

These sample criteria effectively represent real-world tracking impacts with guardrail end terminals and guardrail face. All impact angles are included; shallow-angle redirective impacts to the guardrail face and head-on impacts to the end terminal representative of testing requirements, as well as tracking impacts to the face or terminal at higher angles.

For each vehicle which met these criteria, the injury level of each occupant was recorded. The Abbreviated Injury Scale (AIS) is an anatomically-based injury severity scale created and maintained by the Association for the Advancement of Automotive Medicine (AAAM). Injuries are separated into different body regions and are graded from 1 (minor) to 6 (unsurvivable) based on threat to life (7). Occupants were classed as “seriously injured” if their maximum AIS score was 3 or greater. This includes any fatalities due to crash injuries occurring within 30 days of the crash. A crash was considered to be an injury crash if at least one vehicle occupant was seriously injured. Any occupants with an unknown injury level or that were not seated in a conventional seat (e.g. riding in a trunk or the bed of a pickup, seated on the floor between seats, using a child seat, etc.) were excluded from the analysis.

Vehicles were classified as either cars or light trucks /vans (LTVs). ‘Car’ included NASS body type codes 1 – 11, 13 and 17. ‘LTV’ included NASS body type codes 14 – 16, 19 – 22, 28, 30 – 33, 39 – 42 and 45. Any vehicles which did not fall into either of these categories were excluded from the analysis.

Guardrail crashes were identified using the highest-severity event or rollover-initiation event to ensure that any injuries observed were the direct result of contact with the guardrail. Prior studies (1,8,9) have observed that in about half of all cases where guardrail is struck, it is not the most harmful event. It is therefore extremely important to select only cases where guardrail was the most harmful event, as
doing otherwise would include many injuries caused by secondary impacts and strongly distort the results. While proper vehicle containment and redirection are important aspects of guardrail function, the focus of this analysis is on injury risk directly resulting from guardrail contact.

NASS-CDS codes very limited information pertaining to roadside barrier systems, but generally has extensive crash site photographs. It was therefore necessary to manually inspect crash site photographs to determine:

- If impact was with the end terminal or the guardrail face;
- What type of guardrail was contacted (if any);
- What type of end terminal was contacted (again, if any);
- If the struck portion of the guardrail had been replaced prior to crash site investigation.

A crash was considered to have involved the end terminal if the vehicle made any direct contact with the literal end of the guardrail system. By corollary, guardrail face crashes were any crashes where the vehicle did not make direct contact with the guardrail end. Crashes to the guardrail face not making contact with the rail terminus but still impacting before the 3rd post were coded as face crashes. If it could not be determined whether a crash involved the face or the end terminal as per the above definitions, that crash was excluded from the sample. Crashes at concrete barrier – metal guardrail junctions were excluded from the analysis, as these are complex regions which bear separate analysis from normal length-of-need and end terminals.

Impact attenuators (“crash cushions”) and concrete barriers were sometimes coded as guardrail in NASS-CDS. Any crashes with impact attenuators or concrete barriers were excluded. One of the codes used for guardrail also pertains to improvised or nonstandard barriers; these were discarded as well whenever they were found.

Determining the exact end terminal system involved in a crash from NASS scene photos can be very difficult, as some differences between terminal systems are very subtle. Terminals were therefore only divided into designs which have successfully met some level of the NCHRP Report 350 safety requirements and those which have not. All NCHRP-350-compliant energy-absorbing designs were straightforward to identify, as they all use a conspicuous impact head of some kind. Compliant, non-energy-absorbing designs can be more difficult to tell apart from non-compliant designs, requiring knowledge of specific differences, but there are only a few such designs in common use (Eccentric Loader Terminal, Modified Eccentric Loader Terminal, Slotted Rail Terminal, Vermont Low-Speed End Treatment, burial-in-backslope, three-strand cable terminal). Non-compliant terminals include turndowns, Breakaway Cable Terminals (BCTs), blunt ends and other non-energy-absorbing, non-compliant end treatments. BCTs have a cable and only two breakaway posts, with no strut connecting the first two posts at ground level. Turndowns are obvious, and other non-compliant end treatments lack cables, breakaway posts and ground struts. Although the Manual for Assessing Safety Hardware (MASH) supplanted NCHRP 350 in 2009, “compliant” hardware in this study refers specifically to NCHRP 350 compliant hardware, since the sample period ends prior to the adoption of MASH.

For some cases, the terminal shown in the scene photographs was a replacement for the terminal which was involved in the crash. In practice, damaged guardrails and end terminals are frequently replaced with the same system as the original. However, older systems which are not compliant with current testing criteria are sometimes upgraded to newer systems which are compliant. In this analysis, whenever a replacement terminal was of a non-compliant design it was assumed that the original was non-compliant as well. However, this could not be safely assumed when a replacement terminal was of a compliant design (unless enough of the original terminal was present to positively identify it). Analyses involving end terminal type were therefore run three ways: 1) assuming that all questionable terminals were non-compliant, 2) assuming that they were compliant and 3) excluding questionable terminals from the sample. In a very small number of cases, terminals could not be positively classified from the case photos (e.g. damaged terminals buried in snow, cases where the terminal had simply been removed.
without any type of replacement, case photos taken from a moving vehicle or at great distance). These cases were treated the same as cases where the ambiguity stemmed from terminal replacement. While NASS-CDS scene photographs are often sufficient to identify different end terminals, determining the NCHRP 350 compliance of longitudinal barrier systems is substantially more challenging. CDS scene photographs frequently do not capture sufficient detail to definitively identify specific systems, or may not depict all features necessary to definitively establish compliance. Additionally, estimation of site grade or rail height is not possible without detailed photo analysis. Hence, this analysis only considers NCHRP 350 compliance for end terminals.

Statistical Analysis

All statistical analysis was performed in SAS v9.2. NASS-CDS sample weights, strata and clustering were taken into account to produce nationally representative estimates. Logistic regression on occupant injury level (and other nominal factors of interest) was performed using PROC SURVEYLOGISTIC, and the statistical significance (p-value) of model parameters evaluated via the Wald Chi-Square test (part of the standard SURVEYLOGISTIC output). “Statistical significance” henceforth refers to a 95% confidence level.

RESULTS

Sample Composition

Table 1 breaks down the sampled occupants by the area of the guardrail system struck, occupant role and bodystyle of the occupied vehicle. The final sample used in the analysis contains 1079 occupants distributed across 711 vehicles. A total of 97 entire vehicles were excluded from the sample. These included 32 cases where concrete barrier was miscoded as guardrail, 18 cases where the object struck was a crash cushion, 13 cases where miscellaneous non-guardrail objects were contacted, 5 cases where contact was with a junction between guardrail and concrete barrier, 10 cases whose impact location could not be determined, 6 guardrail-initiated rollovers where the rollover initiation object was not actually a guardrail, 5 guardrail-initiated rollovers where the guardrail impact was not sufficiently damaging to be coded as an impact event in NASS-CDS, 1 guardrail-initiated rollover where the coded rollover object was highly questionable (case 1997-8-15), 1 case where there appears to have been no guardrail contact at all and 7 cases with case weights of zero. A case weight of zero in NASS indicates a crash which was not part of the standard NASS-CDS sampling plan and hence cannot be used to compute national estimates. In addition to these entire cases, 123 individual occupants were excluded from the analysis. One hundred and eight (108) were excluded for having unknown injury levels and 15 more for non-standard seating positions.

Table 1 Breakdown of Sampled Occupants by Area of Guardrail Impacted, Occupant Role, Vehicle Bodystyle and Lateral Area of Vehicle Sustaining Damage

<table>
<thead>
<tr>
<th></th>
<th>n Sample Occupants (unweighted)</th>
<th>% Population Occupants (weighted)</th>
<th>n Sample Vehicles (unweighted)</th>
<th>% Population Vehicles (weighted)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Object Struck</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Guardrail Face</td>
<td>865</td>
<td>89.0 %</td>
<td>569</td>
<td>87.0 %</td>
</tr>
<tr>
<td>Compliant Terminal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Replaced</td>
<td>32</td>
<td>1.3 %</td>
<td>21</td>
<td>1.5 %</td>
</tr>
<tr>
<td>Unknown</td>
<td>6</td>
<td>0.04 %</td>
<td>2</td>
<td>0.03 %</td>
</tr>
<tr>
<td>Original</td>
<td>42</td>
<td>3.2 %</td>
<td>30</td>
<td>4.4 %</td>
</tr>
<tr>
<td>Non-Compliant Terminal</td>
<td>117</td>
<td>6.36 %</td>
<td>82</td>
<td>7.0 %</td>
</tr>
<tr>
<td>Unknown Terminal</td>
<td>17</td>
<td>0.1 %</td>
<td>7</td>
<td>0.07 %</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>1079</td>
<td>100 %</td>
<td>711</td>
<td>100 %</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Occupant Role</th>
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<tbody>
<tr>
<td>Driver</td>
<td>706</td>
<td>66.7 %</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Passenger</td>
<td>373</td>
<td>33.3 %</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1079</strong></td>
<td><strong>100 %</strong></td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bodystyle of Occupied Vehicle</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Car</td>
<td>681</td>
<td>76.0 %</td>
<td>463</td>
<td>75.8 %</td>
</tr>
<tr>
<td>LTV</td>
<td>398</td>
<td>24.0 %</td>
<td>248</td>
<td>24.2 %</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1079</strong></td>
<td><strong>100 %</strong></td>
<td><strong>711</strong></td>
<td><strong>100 %</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Primary Lateral Area of Vehicle Face Damaged</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Left</td>
<td>133</td>
<td>10.3 %</td>
<td>89</td>
<td>12.5 %</td>
</tr>
<tr>
<td>Center</td>
<td>7</td>
<td>0.2 %</td>
<td>5</td>
<td>0.1 %</td>
</tr>
<tr>
<td>Right</td>
<td>147</td>
<td>13.6 %</td>
<td>106</td>
<td>15.8 %</td>
</tr>
<tr>
<td>Left + Center</td>
<td>126</td>
<td>6.1 %</td>
<td>79</td>
<td>6.6 %</td>
</tr>
<tr>
<td>Center + Right</td>
<td>63</td>
<td>3.5 %</td>
<td>39</td>
<td>4.0 %</td>
</tr>
<tr>
<td>Left + Center + Right</td>
<td>517</td>
<td>60.5 %</td>
<td>333</td>
<td>54.1 %</td>
</tr>
<tr>
<td>Unknown</td>
<td>86</td>
<td>5.8 %</td>
<td>60</td>
<td>6.9 %</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1079</strong></td>
<td><strong>100 %</strong></td>
<td><strong>711</strong></td>
<td><strong>100 %</strong></td>
</tr>
</tbody>
</table>

**Vehicle Body Style**

Odds of injury in frontal guardrail crashes were observed to be 1.9 times higher for LTVs than for cars. However, this observed difference was not statistically significant (p-value 0.1867). Both types of vehicle were well represented in the sample. Gabler and Gabauer (10) similarly observed that LTVs presented an elevated risk of fatality compared to cars when all guardrail crashes (not just frontal) are considered in aggregate. However, they did not comment on this finding or discuss its statistical significance. This stands in contrast to the findings of Johnson and Gabler (11) for side crashes with guardrail which found that cars presented greater injury risk than LTVs; that finding was statistically insignificant as well.

**Area of Guardrail Struck**

Figure 1 shows the distribution of exposure and injury crashes by the area of the rail system contacted. The sampled data provides evidence that injury risk differs between frontal terminal impacts and guardrail face impacts. This comparison indicates that the odds of injury are 2.7 times higher in crashes with end terminals than in face crashes. This finding has a p-value of 0.0544, indicating marginal statistical significance. However, when the same comparison is made using individual occupants rather than whole vehicles, the result becomes significant (p-value 0.0424) and injury odds in terminal crashes become 3.0 times higher than in guardrail face crashes. This finding is also consistent with those of (11) for side guardrail crashes.
FIGURE 1 Crashes and serious injuries by area of guardrail contacted. $n_{\text{crash}} = 711$, $n_{\text{injury}} = 138$.

NCHRP-350 Compliance of End Terminals

Figure 2 shows the distribution of crashes and injuries in frontal end terminal crashes only. Respectively, the plots give the distribution assuming that all ambiguous or questionable terminals were non-compliant (top) and assuming they were all compliant (bottom). When terminals of uncertain compliance were excluded from the comparison (not shown), the distribution was intermediate between the two plots shown. In all three cases, non-compliant end terminals had injury odds between 4.2 and 5.3 times higher than compliant terminals, and in every case the difference was statistically significant.
Airbag Deployment

NASS CDS records information on vehicle airbags from case years 2000 through 2008. Airbag deployment and its effects on injury risk were analyzed using this subset of the main sample, which contains 567 vehicles and 866 occupants. Four-hundred sixty-eight (473) of these vehicles were airbag-equipped, and collectively they carried 716 occupants.

86% of all vehicles in frontal guardrail crashes have one or more airbags equipped. Airbag presence in a vehicle can suggest a better overall safety design compared to non-equipped vehicles. However, the data do not give significant evidence that occupants in airbag-equipped vehicles have lesser odds of injury than in non-equipped vehicles. Odds of injury in non-equipped vehicles are only 2.0 times greater than in equipped vehicles, with a p-value of 0.2561. This is consistent with the findings of Gabauer and Gabler (11) for unbelted occupants with and without airbags.

Out of the 86% of vehicles with airbags equipped, one or more of them deploy in 39% of crashed vehicles. Gabauer and Gabler (11) found that airbags deployed in 61% of all non-concrete longitudinal barrier crashes involving airbag-equipped vehicles, which is substantially more frequent than this. However, (11) examined only single-event crashes, while this study included crashes with multiple events. When only single-event, airbag-equipped crashes are considered (n=146), airbags are observed to
deploy in 62.6% of instances which is almost identical to (11). In airbag-equipped guardrail crashes with two events (n=181), airbags deploy in 38.1% of crashes. With three or more events (n=141), airbags deploy in 18.9% of crashes. It is possible that, on average, multiple-event crashes have multiple events because the departure speed was higher, or because each individual impact was less severe, dissipating a smaller portion of the vehicle speed and thus less likely to deploy airbags.

The data also shows that odds of injury when frontal airbags deploy is 10 times greater than when no deployment occurs. The result is very nearly statistically significant, having a p-value of 0.0520. This is to be expected as airbag deployment occurs in higher severity crashes with a higher chance of injury. No significant evidence was found for any difference in airbag deployment rate between cars and LTVs.

Airbag Deployment versus Area of Guardrail Contacted

For airbag-equipped vehicles, odds of airbag deployment are observed to be 3.0 times greater in terminal crashes than in guardrail face crashes. This finding approaches statistical significance (p-value 0.1082), which suggests that a larger sample might possibly render the effect significant. Crashes to the guardrail face tend to redirect vehicles back into the lane of travel, while crashes to terminals tend to arrest forward vehicle motion. This would explain a difference in airbag deployment rate, as airbag deployment is controlled by vehicle velocity change.

The data gives no indication of a significant difference in deployment between compliant and non-compliant end terminals. This may simply indicate that crashes with any narrow, fixed object are highly likely to deploy airbags, or that any difference in deployment rate between compliant and non-compliant terminals is too small to be discerned in this sample.

Rollover Initiation

Rollover is observed to occur in 9.2% of all frontal guardrail crashes. When rollover does occur, Figure 3 shows the breakdown of initiation mechanism. NASS-CDS investigators code the object that, in their best judgment, was responsible for initiating a rollover when one occurs. When the rollover object was coded as a guardrail and no other guardrails were struck between the high-severity guardrail impact and the rollover event, a rollover was considered “tripped by guardrail”. Sampled crashes with rollover coded as the high-severity event were all considered tripped by the last guardrail impact prior to the rollover.

Forty-nine percent (49%) of rollovers in frontal guardrail crashes were initiated by the guardrail itself, while most of the remainder were tripped by objects contacted after the guardrail. Figure 4 shows the distribution of guardrail-initiated rollover by vehicle bodystyle. Odds of rollover were observed to be 7.4 times higher for LTVs than for cars; this result is highly statistically significant (p-value 0.0017). This finding is consistent with the fact that LTVs generally have higher centers of gravity and similar results have been reported in numerous other studies. Gabler and Gabauer (10) found that LTVs had 3 times the rollover probability of cars, which corresponds to 3.7-times greater odds of rollover. While this is consistent with our findings, it is a much smaller effect than was observed here.
FIGURE 3 Distribution of investigator-coded rollover initiation object. \( n_{\text{rollover}} = 145. \)

*Rollover Initiation by Area of Guardrail Contacted*

Figure 4 also shows guardrail-initiated rollover by area of the guardrail system contacted. End terminal contact was observed to have 6.7 times greater odds of initiating rollover than guardrail face contact. This result was highly significant (p-value 0.0101). When this analysis is performed on cars and LTVs separately, rollover odds for terminal contact are 2.5 times greater than for guardrail face contact for cars (p-value 0.2497; not significant) and 7.2 times greater for LTVs (p-value 0.0136). This is also consistent with the higher centers of gravity of LTVs. NCHRP 350 compliance of end terminals was not observed to have any statistically significant effect on rollover risk.
FIGURE 4 Guardrail-initiated vehicle rollover by vehicle bodystyle (guardrail face and terminals combined) and by area of rail system contacted (cars and LTVs combined). \( n_{\text{crash}} = 711, n_{\text{rail rollover}} = 76. \)

### High-Risk Cofactors

Rollover is known to be an extremely high-risk crash mode in and of itself, so it is useful to separate the effect of rollover from that of frontal guardrail impact by itself. Similarly, non-use of seatbelts is also a known high-risk cofactor in crashes of all modes. Figure 5 shows the distribution of all crashes and injury crashes broken down by the presence of rollover and/or non-use of seatbelts. In 75 % of crashes, all vehicle occupants wear their seatbelts and are not involved in rollovers, but these account for just 39 % of the crashes resulting in injury. The remaining 25 % of crashes which involve rollover or have occupants which are unbelted or ejected, or some combination thereof account for the remaining 61 % of injurious crashes. Odds of an injury crash were observed to increase by a factor of 5.1 when any of these high-risk cofactors was present, and the result was statistically significant (\( p\)-value = 0.0043). Note that all vehicle
occupants are belted in about 81% of crashes, which is consistent with the national average belt use rate of 83% reported in Gabler and Gabauer (12) for airbag-equipped vehicles (recall that most of vehicles in this sample were airbag equipped).

**FIGURE 5 Injury versus high-risk cofactor presence. n_{crash} = 711, n_{injury} = 138.**

Reexamining the effect of bodystyle using only cases without high-risk cofactors present, LTV occupants were observed to have 2.1 times the injury odds of car occupants (p-value 0.4054). The disparity is effectively the same as when cofactor-involved cases are included and the result is still statistically insignificant. As discussed previously, this finding is consistent with the findings of Gabler and Gabauer (10), but the lack of statistical significance casts doubt on its meaningfulness.

Figure 6 shows the reanalysis of injury odds and area of the guardrail system contacted. With high-risk cofactors removed, terminal contact now carries 5.1 times greater odds of serious injury than contact with the guardrail face (compared to 2.9 times with cofactors included). As was the case with high-risk cofactors present, the result is marginally significant, having a p-value of 0.0563. As was also the case with high-risk cofactors present, the result becomes statistically significant when occupants and their injuries are considered individually. Odds of an individual occupant being injured are 3.3 times higher in terminal crashes than in crashes to the guardrail face, with a p-value of 0.0248. The increase in the disparity in injury risk between terminals and guardrail face when high-risk cofactors are removed shows that high-risk cofactors tend to mask the effect of area struck.
FIGURE 6 Injury crashes by area of guardrail system contacted, excluding crashes with high-risk cofactors. \( n_{\text{crash}} = 390, n_{\text{injury}} = 32. \)

Figure 7 shows the analysis of end terminal type versus injury risk with cofactor-involved crashes excluded. The top plot treats all questionable terminals as non-compliant; this approach gives non-compliant terminals 11 times greater injury odds than compliant terminals. The difference was observed to be statistically significant (p-value 0.0382). Excluding questionable terminals entirely (not shown) gives a higher odds ratio (15, non-compliant versus compliant) and a similarly significant p-value of 0.0258. The bottom plot treats all questionable terminals as compliant. This approach gives non-compliant terminals 19 times greater injury odds than compliant terminals and, as with the other two comparisons, finds the difference to be statistically significant (p-value 0.0078). Compare these findings to the odds ratios computed with high-risk cofactors included (Figure 2); with cofactors removed, the difference in injury risk between non-compliant and compliant terminals is anywhere between two and almost 5 times as great.
Unknown Terminals Assumed Non-Compliant

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Unknown Terminals Assumed Compliant

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<tbody>
<tr>
<td>Serious Injury Terminal Crashes</td>
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</tbody>
</table>

**FIGURE 7** Injury crashes versus end terminal compliance, end terminal crashes with high-risk cofactor crashes removed. Questionable terminals classed as ‘non-compliant’. \( n_{\text{crash}} = 70, n_{\text{injury}} = 11. \)

**Occurrence of Spearing**

Spearing, or penetration of the guardrail into the vehicle, sometimes occurs in guardrail impacts and can result in very severe injuries when it does happen. But how frequently does spearing actually occur with current end treatments? Out of the 711 crashes examined in this study, only three were found that involved spearing. These cases are shown in Figure 8: NASS-CDS cases 2005-45-104 (case 1, top), 2006-47-34 (case 2, middle) and 2003-73-34 (case 3, bottom). In total, these three cases represent 0.084% of all frontal guardrail crashes and about 0.6% of all frontal end terminal crashes; spearing appears to be a very rare occurrence. In cases 1 and 2, the guardrail penetrated the occupant compartment and caused serious injury, while in case 3 the guardrail only penetrated the engine bay and no serious injury occurred. Cases 1 and 3 both involved end terminals which were not compliant with NCHRP 350. In case 2, the compliance of the end terminal could not be determined.
FIGURE 8 Out of 711 cases in the sample, only three were found where spearing had occurred.
CONCLUSIONS

This analysis examined the effect of a number of factors on injury risk in frontal guardrail crashes. Vehicle bodystyle is not observed to have a statistically significant influence on injury risk directly in this crash mode, although the point estimates for the differences that were observed were consistent with prior studies of the modern vehicle fleet (10). LTVs were observed to have odds of rollover 7.4 times higher than cars in guardrail crashes. There is significant evidence that frontal crashes to end terminals carry inherent injury odds 5.1 times greater than frontal crashes to the guardrail face. Additionally, odds of injury in frontal end terminal crashes appear to be between 11 and 19 times lower when the terminal design is compliant with NCHRP 350, compared to non-compliant designs. High-risk cofactors are associated with 25% of all frontal guardrail crashes, yet are associated with 61% of those resulting in serious injury. Odds of an injury crash are significantly elevated when one or more high-risk cofactors are present and this is observed to mask the effect of other factors.

Airbags were present in about 86% of vehicles in frontal guardrail crashes, and deployed in about 39% of equipped vehicles. Airbag deployment in frontal guardrail crashes appears to be a strong function of the number of total impact events. Airbag deployments are correlated with high crash severity and consequently increased injury risk. The data go on to suggest that odds of airbag deployment may be about 2.9 times greater for end terminal contact than for contact with the guardrail face. However, the data fall short of statistical significance. End terminal compliance with NCHRP 350 does not appear to have any discernable effect on airbag deployment.

Rollover occurs in 9.2% of all frontal guardrail crashes, and is initiated by the guardrail in roughly 49% of instances. The evidence indicates that end terminal contact increases rollover odds by 6.7 times compared to guardrail face contact. Again, the data also indicates that LTVs have 7.4 times greater odds of guardrail-initiated rollover than cars. Both of these findings are statistically significant. When terminal contact and guardrail face contact are compared for cars and LTVs separately, terminals are seen to have rollover odds 2.5 times greater than the guardrail face for cars and 7.2 times greater for LTVs. Only the comparison with LTVs was statistically significant. NCHRP 350 compliance of end terminals was not observed to have any significant effect on rollover propensity.

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REFERENCES