



U.S. Department
of Transportation
**National Highway
Traffic Safety
Administration**



DOT HS 810 847

October 2007

The Role of Vertical Roof Intrusion and Post-Crash Headroom in Predicting Roof Contact Injuries to the Head, Neck, or Face During FMVSS No. 216 Rollovers; An Updated Analysis

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1. Report No. DOT HS 810 847		2. Government Accession No.		3. Recipients's Catalog No.	
4. Title and Subtitle The Role of Vertical Roof Intrusion and Post-Crash Headroom in Predicting Roof Contact Injuries to the Head, Neck, or Face During FMVSS No. 216 Rollovers: An Updated Analysis				5. Report Date October 2007	
				6. Performing Organization Code NVS-421	
7. Author(s) Alexander Strashny, Ph.D.				8. Performing Organization Report No.	
9. Performing Organization Name and Address Mathematical Analysis Division, Office of Traffic Records and Analysis National Center for Statistics and Analysis National Highway Traffic Safety Administration U.S. Department of Transportation NVS-421, 1200 New Jersey Avenue SE. Washington, DC 20590				10. Work Unit No. (TRAIS)n code	
				11. Contract of Grant No.	
12. Sponsoring Agency Name and Address Mathematical Analysis Division, Office of Traffic Records and Analysis National Center for Statistics and Analysis National Highway Traffic Safety Administration U.S. Department of Transportation NVS-421, 1200 New Jersey Avenue SE. Washington, DC 20590				13. Type of Report and Period Covered NHTSA Technical Report	
				14. Sponsoring Agency Code	
15. Supplementary Notes I thank Chou-Lin Chen, Rajesh Subramanian, Rory Austin, Larry Blincoe, Stephen Summers, Chuck Kahane, and the peer reviewers for their help.					
16. Abstract The purpose of this report is to use the National Automotive Sampling System Crashworthiness Data System (NASS CDS) data for years 1997 through 2005 to determine whether there was a statistically significant relationship between the maximum severity of head, neck, and face injuries due to occupant roof contact that occurred in rollovers that were likely to be covered by Federal Motor Vehicle Safety Standard No. 216 and either post-crash headroom or vertical roof intrusion. The report uses the ordered probit and binary probit models, both unadjusted and adjusted for potentially confounding factors, to establish the existence of statistically significant relationships. The report presents estimates of 24 different models, 12 for intrusion and 12 for headroom. In all 24 models, the relationship between injury severity and the explanatory variable (intrusion or headroom) was statistically significant.					
17. Key Words Post-crash headroom, vertical roof intrusion, rollover, quarter turns, roof crush, end-over-end, rollover severity, roof impact, roof-to-ground contact, roof-to-ground exposure, ordered probit				18. Distribution Statement Document is available to the public through the National Technical Information Service, Springfield, VA 22161	
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No of Pages	22. Price

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Executive Summary

Objective. The purpose of this report is to use the National Automotive Sampling System Crashworthiness Data System (NASS CDS) data for years 1997 through 2005 to determine whether there was a statistically significant relationship between the maximum severity of head, neck, and face injuries due to occupant roof contact that occurred in rollovers that were likely to be covered by Federal Motor Vehicle Safety Standard No. 216 (FMVSS No. 216) (“relevant injuries”) and either post-crash headroom or vertical roof intrusion. The report is not intended to make specific recommendations for changes to FMVSS No. 216, nor is it intended to calculate benefits from any such change. Instead, the conclusions in this report are meant to provide a basis and rationale for further analysis.

Method. The report uses NASS CDS data for years 1997 through 2005. It also uses data furnished by Consumers Union to estimate pre-crash headroom. It uses the ordered probit and binary probit models, both unadjusted and adjusted for potentially confounding factors, to establish the existence of statistically significant relationships.

Result. The report presents estimates of 24 different statistical models, 12 for intrusion and 12 for headroom. In all 24 models, the relationship between injury severity and the explanatory variable (intrusion or headroom) was statistically significant. In 22 of the 24 models, the p-value was less than 0.0001; in two of the models, the p-value was 0.0009 or less.

Conclusion. This report shows that a statistically significant relationship existed between both vertical roof intrusion and post-crash headroom on the one hand and maximum injury severity of head, neck, or face injury from roof contact on the other hand. The relationship remained regardless of the statistical model used. In particular, the report used both unadjusted and adjusted models, both with continuous and dichotomous versions of the explanatory variables, and with multilevel or bilevel versions of the dependent variable, and still the relationship remained statistically significant.

Introduction

Background and purpose. Austin et al. (2005) use data from the NASS CDS for the years 1997 through 2001 to illustrate the existence of a statistically significant relationship between maximum severity of head, neck, and face injuries due to occupant roof contact that occurred in rollovers that were likely to be covered by FMVSS No. 216 and the headroom remaining over the occupant after the crash (“post-crash headroom” or simply “headroom”). Relevant occupants were age 13 and older, sat in the two front outboard seats, were belted, and were neither completely nor partially ejected. Relevant rollovers were single-vehicle passenger-vehicle rollovers that involved roof-to-ground exposure (that is, two or more quarter turns in sideways rollovers), as well as end-over-end rollovers, excluding convertibles and vehicles before model year 1987. A draft of that report was peer-reviewed by Flannagan et al. (2005). The final report addressed and incorporated reviewers’ comments. The comments were also specifically addressed by NHTSA in a separate document, NHTSA (2005).

Austin et al. (2005) find a statistically significant relationship between injury severity and whether post-crash headroom was positive or negative. They did not, however, find a statistically significant relationship between injury severity and headroom as a continuous variable, nor did they find a statistically significant relationship between injury severity and the amount of vertical roof intrusion over the occupant seating position (“intrusion”).

The purpose of this report is to extend Austin et al. (2005) using more recently available data, namely, the purpose is to use NASS CDS data for years 1997 through 2005 to determine whether there was a statistically significant relationship between the maximum severity of relevant injuries and either headroom or intrusion, both as dichotomous and as continuous variables. The report is not intended to make specific recommendations for changes to FMVSS No. 216, nor is it intended to calculate benefits from any such change. Instead, the conclusions in this report are meant to provide a basis and rationale for further analysis.

Data. Much of the following discussion of the data is taken verbatim from Austin et al. (2005). Some adjustments have been made, such as for more recent years available in the database. Also, more detailed discussions of certain issues are presented.

The primary data set used for this analysis is NASS CDS for years 1997 through 2005. NASS CDS is a complex, random sample of crashes involving at least one passenger car or “light truck or van” (LTV), defined by a gross vehicle weight rating of 4,536 kilograms (10,000 pounds) or less, that was towed due to damage. The beginning year of 1997 was selected because it was the first year that NASS CDS coded continuous intrusion measures. Prior to that year, NASS CDS coded intrusion in categories with ranges that were too wide to be of use in this study. The ending year of 2005 was the most current year available at the time of this analysis. Note that the database codes intrusion in centimeters. To make results in this report comparable to those in Austin et al. (2005), measurements have been converted from centimeters to inches. This study focuses on automobiles, utility vehicles, light pickup trucks, and light vans that were involved in single-vehicle rollover crashes. The decision to restrict the analysis to single-vehicle crashes is to minimize confounding factors and to increase the purity of the analysis. In addition,

convertibles and vehicles with a model year earlier than 1987 have been excluded because of the lack of (pre-crash) headroom measures.

Additional restrictions were applied to the data to identify crashes that are most closely related to FMVSS No. 216, “Roof crush resistance.” Vehicles that experienced any fixed-object collisions, such as a collision with a tree, causing damage to their tops or that rolled only one-quarter turn to the side, and thus did not have roof-to-ground contact, were excluded. Both of these situations are outside of the scope of the rollovers currently addressed by FMVSS No. 216. Following Austin et al. (2005), “fixed object” means CDS classifications of “fixed object,” other than shrubbery, bush, or embankment, or CDS classification of “nonbreakaway pole or post,” other than ditch, culvert, or ground. Two other restrictions were that the vehicle must not have been towing a trailing unit or that it must not be a multistage or certified altered vehicle because changes may have been made to the roof structure.

The occupants of interest for this analysis were seated in one of the two outboard front seats (seating positions 11 and 13). The analysis was further restricted to belted occupants who were not ejected, either totally or partially, and who were 13 or older. It is believed that the injury patterns for ejected (both totally and partially) and unbelted occupants differ substantially from those of belted occupants, and their inclusion would complicate the analysis. The primary reason for excluding children 12 and under is due to NHTSA recommendation that children 12 and under should be placed in the back seat whenever possible. Secondly, there is uncertainty in reasonably estimating the pre-crash headroom for children 12 and under due to variables such as child restraint system characteristics.

Only occupants who are known not to have been ejected were included in the analysis. Occupants who were totally ejected, partially ejected, ejected to an unknown degree, or whose ejection status is unknown, were not included in the analysis. The two main reasons why only non-ejected occupants were included in the analysis are:

1. This report was done to support prospective rulemaking for FMVSS No. 216. NHTSA is currently working under a SAFETEA-LU mandate for ejection mitigation. The ejected occupants in rollover will be considered separately in this rulemaking. The Office of Management and Budget (OMB) does not permit “double-counting” of safety benefits. Ejected occupants are more appropriately considered in the context of the ejection mitigation rulemaking.
2. The report is meant to perform analysis that is comparable to the analysis performed in Austin et al. (2005), which does not include partially ejected occupants in its analysis.

One rationale for only considering restrained occupants was that a reduction in roof intrusion is less likely to prevent occupant-to-roof contacts for unrestrained occupants. The consideration of restrained occupants only makes the safety estimates more reliable, but also more conservative. This is consistent with NHTSA’s best practices.

The effects of a rollover are different on restrained and unrestrained occupants. Bidez et al. (2005), citing other reports, state the following regarding this difference (emphases added):

Although some industry representatives still dispute any relationship between vehicle design and injury causation in rollover crashes, according to Digges et al. (1994), "...significant portions of the HARM (in rollover crashes) are associated with head/brain and spinal injuries from contact with the roof and upper interior structure." **Moreover, restrained occupants are at higher risk of HARM from roof and rail/header contacts than unrestrained occupants. (Digges et al., 1994)** "Reductions in the severity of contacts which produce injury can be achieved by reducing the relative displacement between the occupant and the surface contacted and by providing a yielding 'friendly' surface." ...

Published biomechanical studies suggest that cervical spine preflexion yields a greater incidence of lower cervical compression and burst fractures than neutrally positioned spines (Pintar et al., 1990, 1995). **Restrained occupants in rollover collisions are typically pre-flexed, due to the initial locking of their belt restraint system, and thus are at higher risk of cervical spine injury in the presence of an intruding roof structure when compared to unrestrained occupants. Ford, for instance, recognized the increased risk to belted occupants in rollover crashes as early as the 1970s when it first began serious investigations into vehicle rollover countermeasures. This higher risk of serious head and/or spine injury with roof impact for restrained versus unrestrained occupants in rollovers was confirmed with U.S. field accident data (Digges et al., 1994).**

Finally, another simple reason for only considering restrained occupants is that Austin et al. (2005), which this report is building upon, does likewise.

Post-crash headroom was estimated as the estimated pre-crash headroom minus intrusion. Pre-crash headroom was estimated from the data obtained from the Consumers Union,¹ adjusted by seated occupant height. Following Austin et al. (2005), seated occupant height was estimated as 0.48 times total occupant height.

The dependent variable considered in this report is the maximum severity of head, neck, and face injuries due to contact with a roof component. Using the NASS CDS occupant injury file, identified injuries to the head, neck, or face are identified using the body region variable. The intention of using head, neck, and face injuries related to roof contact was to identify injuries that were most likely to be affected by a reduction in headroom for belted occupants. While not as common as head or neck injuries, facial contact with a roof component, particularly the A and B pillars, can occur during a rollover. The injuries include direct contact injuries as well as induced or indirect contact injuries.² For each injury, NASS CDS codes an injury source from the findings of NHTSA's trained crash investigators. The decision is based upon inspection of the vehicle, a review of the medical records, and interviews with surviving occupants. The injury was classified as contact with a roof component if the injury source was the A pillar, B

¹ Consumers Union is an independent nonprofit organization whose stated mission is "to test products, inform the public and protect consumers." For more information, see <http://www.consumerreports.org>.

² A direct contact injury results from a force impact directly on the injured body region by the injury source component. An indirect contact injury results from a force transmitted from the injury source component through another body region to the injured region. For example, an indirect contact neck injury may occur when the force is transmitted through the head.

pillar, front or rear header, roof side rail, or the roof itself. The A- and B-pillars are included because dynamic rollover testing indicates frequent occupant-to-roof impacts at the top of the A- and B-pillars where they connect with the roof. Also in “matchbox” type failures where the roof shears sideways, the occupant contact related to the roof crush is often with the vehicle pillars or side rail. Injury severity is measured on the Abbreviated Injury Scale (AIS). The AIS is a seven-level scale for classifying injuries, based on the threat to life, with higher levels associated with more serious injuries. In order of increasing severity, the injury scale is: not injured (0), minor (1), moderate (2), serious (3), severe (4), critical (5), and maximum (untreatable) (6).

When the values of certain variables that are required in the analysis are unknown, the entire observation must be removed from the analysis. Following Austin et al. (2005), the sample weights of the remaining observations are inflated such that the estimated number of cases does not change after the removal of observations.

When considering the dependent variable of maximum injury severity of all head, neck, and face injuries from contact with a roof component, occupants who did not have a roof contact injury to the head, neck, or face were assigned an AIS of 0 (uninjured). The distribution of the dependent variable is shown in Table 1. For comparison, the table also shows the distribution as reported in Austin et al. (2005).

Table 1. Distribution of the maximum injury severity of all head, neck, and face injuries from contact with a roof component.

	Maximum Severity of Head, Neck, or Face Injury From Roof Contact					
	Current Report (using CY 1997-2005 data)			Austin et al. (2005) (using CY 1997-2001 data)		
	Weighted Percent	Weighted Annual Average	Sample Size	Weighted Percent	Weighted Annual Average	Sample Size
Not Injured (AIS 0)	80.96%	159,181	1,907	84.42%	127,633	522
Minor Injury (AIS 1)	15.55%	30,574	588	12.20%	18,444	158
Moderate Injury (AIS 2)	2.62%	5,145	191	2.78%	4,206	51
Serious Injury (AIS 3)	0.43%	848	60	0.38%	573	20
Severe Injury (AIS 4)	0.12%	237	24	0.16%	246	12
Critical Injury (AIS 5)	0.05%	96	13	0.02%	36	6
Maximum (untreatable) Injury (AIS 6)	0.27%	537	56	0.03%	50	4
Total	100%	196,618	2,839	100%	151,187	773

Source: NHTSA, NCSA, NASS CDS 1997-2005; Austin et al. (2005).

As the table shows, based on the annual average, there were fewer and fewer cases at each higher injury severity. The only exception is that at AIS 6, the highest possible injury severity, there were more cases than at AIS 5. The proportion of cases at each AIS level as used in this report

and as reported in Austin et al. (2005) are very similar. For example, at AIS 3, there was an estimated 0.43 percent of the cases according to this report and an estimated 0.38 percent of the cases according to Austin et al. (2005). However, the sample size in this report is markedly higher than it was in Austin et al. (2005). For example, the sample size for AIS 6 was only 4 observations in Austin et al. (2005) compared to 56 observations in the current report. The sample size for all AIS levels was 773 observations in Austin et al. (2005) compared with 2,839 observations in this report.

Methodology. To achieve the report’s purpose, it estimates several statistical models. Since the dependent variable is measured on an ordinal scale and has more than two levels, an appropriate statistical model for analyzing it is the ordered probit model (also known as the “cumulative probit model”). In addition to modeling multiple levels of injury severity, Flannagan et al. (2005) suggested also modeling whether the injury was AIS 0 or 1 on the one hand or AIS 2 or greater on the other hand. This is done using the binary probit model. The SAS procedure called SURVEYLOGISTIC was used to estimate these models.

While Austin et al. (2005) use cumulative logistic regression in its analysis, there is little difference between logistic and probit models, both in theory and in practice. Analyzing data with either model produces practically the same results. The logistic model, however, could be seen as an approximation of the probit model. Many papers that model injury severity that have been published in the scientific literature in recent years use the ordered probit model. These papers analyze data from a variety of databases on a variety of crash types that have occurred in a variety of localities. Here are a few examples. Khattak et al. (2003) apply the ordered probit model to data from the Highway Safety Information System (HSIS) to model injury severity of occupants involved in single-vehicle large truck rollovers in North Carolina. Austin and Faigin (2003) apply the ordered probit model to data from NASS CDS to investigate occupant injury severity across different age groups. Kockelman and Kweon (2002) apply the ordered probit model to data from the National Automotive Sampling System General Estimates System (NASS GES) to model injury severity in all types of crashes, two-vehicle crashes, and single-vehicle crashes. Pai and Saleh (2007) apply the ordered probit model to data from United Kingdom’s STATS19 database to model injury severity of motorcycle riders in junction-type crashes. Quddus et al. (2002) use the ordered probit model with crash data from Singapore to model injury severity in motorcycle crashes. Duncan et al. (1998) use the ordered probit to model injury severity of passenger car occupants in rear-end collisions between heavy trucks and passenger cars. Abdel-Aty (2003) uses the ordered probit to model driver injury severity in crashes that occurred in central Florida. Finally, Zajac and Ivan (2003) use the ordered probit to model pedestrian injury severity in crashes that occurred in rural Connecticut.

As mentioned, the purpose of this report is to see whether a statistically significant relationship exists between the severity of relevant injuries and either post-crash headroom or intrusion. Therefore, the report uses each one of these as an explanatory variable. They are coded as continuous variables, simply stating the amount, measured in inches, as well as dichotomous variables. A dichotomous variable is set to equal to 1 if the corresponding continuous variable is positive and 0 otherwise. The dichotomous variables are used for two reasons. First, since Austin et al. (2005) were able to establish a relationship between injury severity and dichotomous post-crash headroom, and since this report builds on that report, dichotomous variables are of interest. Second, the values of the dichotomous variables correspond to important physical events –

dichotomous intrusion indicates whether the roof intruded; dichotomous headroom indicates whether the roof hit the occupant.

Some models used only one explanatory variable (intrusion or headroom, whether continuous or dichotomous). These are called “unadjusted” as they have not been adjusted for potentially confounding factors. “Adjusted” models, on the other hand, control for a number of potentially confounding factors. One set of adjusted models control for all the variables that Austin et al. (2005) controls for, namely, number of quarter turns to the side (0 in case of an end-over-end rollover), whether the rollover was end-over-end, occupant age, occupant sex, and whether the vehicle was a passenger car or a light truck or van.

One reason for using adjusted models is to control for rollover severity. According to Eigen (2003), while there is no universally accepted measure of rollover severity, some studies do use the number of quarter turns for this purpose. This is what Austin et al. (2005) does, and that is why this report uses the number of quarter turns in one set of adjusted models. Eigen (2003) also states that rollover severity as experienced by occupants varies with the row in which the occupants are seated. Since this report only considers front seated occupants, there is no need to control for the row.

Following Eigen (2005), define the number of roof-to-ground exposures in a sideways rollover as the number of times that the vehicle roof faced downward, toward the ground, regardless of the number of times that the roof physically contacted the ground. Specifically, in case of an end-over-end rollover, the number of roof-to-ground exposures is set to 0. In case of a sideways rollover, the number of roof-to-ground exposures is defined as 0.25 times the number of quarter turns, rounded to the nearest unit. Thus, 2, 3, 4, and 5 quarter turns correspond to 1 roof-to-ground exposure; 6, 7, 8, and 9 quarter turns correspond to 2 roof-to-ground exposures, and so on. To describe this quantity, defined in terms of quarter turns, other studies, such as Digges and Eigen (2003) and Eigen (2005), use words such as “impact” or “contact”. To avoid confusion, and to emphasize that a roof exposure is not necessarily the same as an actual physical roof-to-ground contact, this report uses the word “exposure”.

Digges and Eigen (2003) and Eigen (2005) state that the number of roof-to-ground exposures is a good measure of rollover severity. Specifically, Digges and Eigen (2003) find that “for belted occupants and unbelted ejected occupants in single vehicle crashes, the number of roof impacts is an appropriate severity indicator.” Since this report considers belted occupants in single-vehicle crashes, according to Digges and Eigen (2003), the number of roof exposures is a good measure of rollover severity. Therefore, another set of adjusted models controls for all the variables used in Austin et al. (2005), except that instead of using the number of quarter turns to the side, they use the number of roof-to-ground exposures. The adjusted models that use quarter turns are called “quarter turn adjusted”; the models that use roof-to-ground exposures are called “roof exposure adjusted”.

It might appear that the number of quarter turns variable and the end-over-end indicator might be highly correlated and that using both of them as explanatory variables in the same model might cause multicollinearity. This is because there is a relationship between the two variables: whenever the end-over-end indicator is equal to 0, the number of quarter turns is greater than or equal to 2; whenever the end-over-end indicator is equal to 1, the number of quarter turns is

equal to 0. In fact, the correlation coefficient between the two variables is just -0.12, which means that the variables are not strongly correlated at all and using both of them as explanatory variables at the same time would not cause multicollinearity. Likewise, the correlation coefficient between the number of roof exposures and the end-over-end indicator is -0.17, which means that these two variables are not strongly correlated either and can both be used in the same model as explanatory variables without causing multicollinearity.

Ordered Probit Model

In this section, the ordered probit is used to model the maximum severity of head, neck, or face injury from roof contact as a function of a number of explanatory variables. Suppose a response variable has k possible ordered responses. In our case, injury severity has $k = 7$ possible ordered responses, namely, AIS 0 through AIS 6. Let α_i be the intercept for category i , $\beta'x$ be a linear combination of coefficients and covariates for a particular case, $\Phi(\cdot)$ be the standard normal cumulative distribution function, and p_i the probability of category i . Then, in the ordered probit model, the probabilities of each possible outcome are determined as follows:

$$p_1 = \Phi(\alpha_1 + \beta'x), \quad (1)$$

$$p_i = \Phi(\alpha_i + \beta'x) - \Phi(\alpha_{i-1} + \beta'x) \text{ for } 1 < i < k, \text{ and } (2)$$

$$p_k = 1 - \Phi(\alpha_{k-1} + \beta'x). \quad (3)$$

Note that Austin et al. (2005) use expressions of the form $\alpha_i - \beta'x$ rather than $\alpha_i + \beta'x$. Because of this, when comparing the estimates of the β coefficients (the coefficients on the explanatory variables, not the intercepts) between the two reports, the estimates from one of the reports should be negated. As used in this report, a positive coefficient means that as the explanatory variable *increased*, injury severity tended to *decrease*. An easy way to remember this is that a positive coefficient is “good,” as an increase in the variable tended to improve injury outcomes.

The explanatory variables that are of primary interest are the amount of roof intrusion and post-crash headroom, all measured in inches. Both the dichotomous variables (1 if the value of the variable was positive, 0 if it was not) and continuous variables (which simply stated the value of the variable in inches) are considered.

Two types of models are used, “unadjusted” and “adjusted.” The unadjusted models are bivariate models in which injury severity is modeled as a function of one of the above explanatory variables. The adjusted models are multivariate models which control for a number of potentially confounding factors. One set of these adjusted models control for all the variables that Austin et al. (2005) controlled for, namely, number of quarter turns to the side (0 in case of an end-over-end rollover), whether the rollover was end-over-end, occupant age, occupant sex, and whether the vehicle was a passenger car or a light truck or van. Another set of adjusted models control for the same variables, except that instead of controlling for the number of quarter turns, they control for the number of roof exposures. As mentioned in the previous section, the number of quarter turns and the end-over-end indicator were not highly correlated, which means that both could be

used as explanatory variables in the same model without danger of multicollinearity. The same applies to the number of roof exposures and the end-over-end indicator.

Table 2 shows coefficient estimates for all the models. Each column represents a different model; each row represents a different variable. Estimated coefficients that were statistically significant at the 0.05 level are shown in bold. Note that the p-values for each of the four explanatory variables of interest (continuous and dichotomous intrusion and headroom) were less than 0.0001, indicating that both intrusion and headroom were statistically significant.

Percent concordant and c are two popular measures of association between estimated probabilities and observed outcomes. Percent concordant can be anywhere between 0 and 100; c can be anywhere between 0 and 1. Higher values of each measure indicate better association.

Table 2. Ordered probit models of maximum injury severity for head, neck or face injuries from roof contact.

		Unadjusted			
		Intrusion		Post-crash headroom	
		cont	dich	cont	dich
Intrusion	cont (inches)	-0.075			
	dich		-0.736		
Post-crash headroom	cont (inches)			0.060	
	dich				0.822
Intercepts	AIS 0	1.20	1.37	0.85	0.35
	AIS 1	2.21	2.35	1.83	1.36
	AIS 2	2.81	2.93	2.42	1.95
	AIS 3	3.06	3.18	2.68	2.21
	AIS 4	3.18	3.30	2.79	2.33
	AIS 5	3.24	3.35	2.85	2.38
% concordant		58.9	29.7	61.7	36.3
c		0.637	0.583	0.633	0.609

		Quarter turn adjusted				Roof exposure adjusted			
		Intrusion		Post-crash headroom		Intrusion		Post-crash headroom	
		cont	dich	cont	dich	cont	dich	cont	dich
Intrusion	cont (inches)	-0.078				-0.075			
	dich		-0.745				-0.709		
Post-crash headroom	cont (inches)			0.068				0.066	
	dich				0.903				0.873
# quarter turns	(end-over-end = 0)	-0.083	-0.085	-0.079	-0.082				
# roof exposures	(end-over-end = 0)					-0.42	-0.42	-0.42	-0.41
End-over-end	(1 = yes / 0 = no)	-0.87	-1.01	-0.86	-0.98	-1.09	-1.21	-1.08	-1.18
Occupant age	(years)	-0.008	-0.005	-0.010	-0.010	-0.009	-0.006	-0.010	-0.010
Occupant sex	(1 = male / 0 = female)	0.14	0.10	0.30	0.26	0.11	0.08	0.27	0.23
Vehicle	(1 = LTV / 0 = car)	0.21	0.19	0.17	0.24	0.17	0.15	0.13	0.20
Intercepts	AIS 0	1.60	1.70	1.19	0.64	1.83	1.92	1.45	0.89
	AIS 1	2.65	2.72	2.22	1.70	2.89	2.95	2.48	1.95
	AIS 2	3.28	3.34	2.84	2.33	3.53	3.57	3.11	2.59
	AIS 3	3.54	3.59	3.10	2.59	3.79	3.82	3.38	2.86
	AIS 4	3.66	3.71	3.22	2.71	3.91	3.94	3.50	2.97
	AIS 5	3.72	3.77	3.28	2.77	3.97	3.99	3.56	3.03
% concordant		64.3	61.1	64.1	63.8	63.9	60.4	63.7	63.5
c		0.655	0.623	0.652	0.648	0.65	0.618	0.648	0.646

Note: Bolded estimates are statistically significant at the 0.05 level.

Source: NHTSA, NCSA, NASS CDS 1997-2005.

As expected, coefficient estimates for intrusion were negative, indicating that an increase in intrusion tended to be associated with an increase in the level of injury severity; the coefficient estimates for post-crash headroom were positive, indicating that an increase in headroom tended to be associated with a decrease in the level of injury severity. In most cases, for both intrusion and headroom, coefficient estimates for the adjusted models were greater in absolute value than the estimates for the corresponding unadjusted models. This means that adjusting for potentially confounding factors usually increased the estimated effect of intrusion and post-crash headroom on injury severity.

The number of quarter turns, the number of roof exposures, and the end-over-end indicator were statistically significant in all of the adjusted models. The estimated coefficients on the number of quarter turns and on the number of roof exposures were negative, indicating that the more quarter turns or roof exposures, the worse the injury severity, as expected. Digges and Eigen (2003) used the CDS database for years 1995 to 2001 to study factors that were associated with injury severity in single-vehicle rollovers for belted non-ejected occupants and found the same effect. Accounting for the different sign conventions between the two reports, the sign of the coefficient on the end-over-end indicator is the same as it is in Austin et al. (2005). An interpretation of the relationship between the coefficients on the number of quarter turns and the end-over-end indicator is discussed below.

Occupant age was statistically significant in the quarter turn and roof exposure adjusted continuous intrusion, continuous headroom, and dichotomous headroom models. In all cases, the coefficient was negative, indicating a tendency toward higher injury severity with increasing age, as expected. This is consistent with Austin et al. (2005). Strashny (2007) studies the probability of fatality in single-vehicle rollovers using the Fatality Analysis Reporting System and GES databases. It finds that higher occupant age was associated with a greater probability of fatality.

Occupant sex was statistically significant in the continuous and dichotomous headroom models. The positive coefficient indicated that, other things being equal (including post-crash headroom), males tended to have lower injury severity than females. However, according to Austin et al. (2005), males tended to have higher injury severity, though the result was not statistically significant. According to the Strashny (2007), males tended to have higher probability of fatality. One possible explanation for this result is as follows. Males tend to be taller than females. Thus, an equal amount of post-crash headroom implies a generally lower amount of intrusion for a male as compared to a female occupant. If injury is primarily associated with the amount of intrusion as opposed to the amount of post-crash headroom, then, given the same amount of headroom, the generally lower amount of intrusion over the male occupants is associated with a lower risk of injury. This explanation is consistent with the fact that, in the intrusion models, the occupant sex variable was not statistically significant.

Finally, vehicle type was only statistically significant in the dichotomous headroom models. The positive coefficient indicated that occupants in light trucks and vans (LTVs) tended to have lower injury severity than occupants in passenger cars. According to Austin et al. (2005), occupants in LTVs tended to have higher injury severity, though the result was not statistically significant. According to Strashny (2007), occupants in LTVs tended to have lower probability of fatality, agreeing with the current report.

Ten of the 12 models shown in Table 2 had about the same association between estimated probabilities and observed outcomes, with percent concordant ranging between about 60 and 65 and c near 0.65. The two exceptions with lower associations were the unadjusted dichotomous intrusion model and the unadjusted dichotomous headroom model. The model with the best association, according to both percent concordant and c measures, was the quarter turn adjusted continuous intrusion model.

Recalling Equations 1-3, and given the estimates in Table 2, here are some sample calculations of probabilities of the various severities of relevant injury. The first example uses the unadjusted continuous intrusion model, the estimates for which are given in the first column with estimates in Table 2. To estimate the probabilities using this model, all one needs to know is the amount of intrusion, measured in inches. For this example, suppose intrusion was 3 inches. Recall that $\Phi(y)$ can be calculated in Excel using the expression =NORMDIST($y,0,1,1$). Then, the estimated probabilities are as follows:

$$\begin{aligned}
 y &= -0.075 * 3 = -0.226 \\
 p(AIS0) &= \Phi(1.20 + y) = 83.6\% \\
 p(AIS1) &= \Phi(2.21 + y) - \Phi(1.20 + y) = 14.0\% \\
 p(AIS2) &= \Phi(2.81 + y) - \Phi(2.21 + y) = 1.86\% \\
 p(AIS3) &= \Phi(3.06 + y) - \Phi(2.81 + y) = 0.27\% \\
 p(AIS4) &= \Phi(3.18 + y) - \Phi(3.06 + y) = 0.07\% \\
 p(AIS5) &= \Phi(3.24 + y) - \Phi(3.18 + y) = 0.03\% \\
 p(AIS6) &= 1 - \Phi(3.24 + y) = 0.13\% .
 \end{aligned}$$

The second example uses the quarter turn adjusted continuous intrusion model. To estimate the probabilities using this model, one needs to know not only the intrusion, measured in inches, but also the values of the other covariates, namely, the number of quarter turns to the side, whether the rollover was end-over-end, occupant age, occupant sex, and vehicle type. For this example, suppose intrusion was 3 inches, there were 4 quarter turns, the rollover was not end-over-end (0), occupant age was 30 years old, occupant sex was male (1), and vehicle type was a car (0). Then, the estimated probabilities are as follows:

$$\begin{aligned}
 y &= -0.078 * 3 - 0.083 * 4 - 0.87 * 0 - 0.008 * 30 + 0.14 * 1 + 0.21 * 0 = -0.677 \\
 p(AIS0) &= \Phi(1.60 + y) = 82.2\% \\
 p(AIS1) &= \Phi(2.65 + y) - \Phi(1.60 + y) = 15.4\% \\
 p(AIS2) &= \Phi(3.28 + y) - \Phi(2.65 + y) = 1.97\% \\
 p(AIS3) &= \Phi(3.54 + y) - \Phi(3.28 + y) = 0.26\% \\
 p(AIS4) &= \Phi(3.66 + y) - \Phi(3.54 + y) = 0.07\% \\
 p(AIS5) &= \Phi(3.72 + y) - \Phi(3.66 + y) = 0.03\% \\
 p(AIS6) &= 1 - \Phi(3.72 + y) = 0.12\% .
 \end{aligned}$$

$\alpha_i + \beta'x$, the expression on which the standard normal cumulative distribution function $\Phi(\)$ in Equations 1-3 operates, is called the latent response. For instance, as is seen from the sample

calculations, the greater the latent response for $i = AIS0$, the greater the probability of no injury (AIS 0). Let β_Q be the coefficient on the number of quarter turns variable and β_E be the coefficient on the end-over-end indicator. Hypothetically, suppose two occupants were in two relevant rollovers that were identical in every way except that one of them was an end-over-end rollover while the other was a sideways rollover with $q \geq 2$ quarter turns. Let z be the difference in the latent response of the occupant who was in a sideways rollover minus the latent response of the occupant who was in an end-over-end rollover. This difference is

$$z = \beta_Q q - \beta_E.$$

The difference z illustrates the estimated hypothetical effect on the latent response of having changed an end-over-end rollover to a sideways rollover with q quarter turns. For example, using the quarter turn adjusted continuous intrusion model, the difference z was estimated to be

$$z = -0.083q + 0.87.$$

Other things being equal, a sideways rollover with q quarter turns would have been hypothetically equivalent to an end-over-end rollover in terms of injury severity if the difference z was 0. This occurs when the number of quarter turns is

$$q^* = \frac{\beta_E}{\beta_Q}.$$

For example, using the quarter turn adjusted continuous intrusion model, $q^* = 10.6$, indicating that, other things being equal, a sideways rollover with about 11 quarter turns was hypothetically equivalent to an end-over-end rollover in terms of injury severity. Sideways rollovers with fewer than q^* quarter turns were better than end-over-end rollovers because the difference z was positive, indicating a higher probability of no injury in the sideways rollover as compared with an end-over-end rollover. Sideways rollovers with greater than q^* quarter turns were worse than end-over-end rollovers because the difference z was negative.

For the four quarter turn adjusted models in Table 2, q^* ranged from 10.6 to 12.0. Since over 99 percent of all occupants who were involved in relevant sideways rollovers were in rollovers with between 2 and 10 quarter turns, this means that, according to the models, other things being equal, an end-over-end rollover was almost always worse than a sideways rollover in terms of injury severity.

The same logic can be applied to the roof exposure adjusted models to determine the number of roof exposures that were hypothetically equivalent to an end-over-end rollover. Let β_R be the coefficient on the number of roof exposures and let r^* be number of roof exposures that were hypothetically equivalent to an end-over-end rollover. Then,

$$r^* = \frac{\beta_E}{\beta_R}.$$

For the four roof exposure adjusted models, r^* ranged between 2.6 and 2.9, indicating that, other things being equal, a sideways rollover with 2 roof exposures was hypothetically less severe than an end-over-end rollover, while a sideways rollover with 3 roof exposures was more severe.

Binary Probit Model

This section performs the same analysis as the previous section, except that it uses dichotomized injury severity at the AIS 2+ cutpoint. For consistency of coefficient signs between these models and those estimated above, probability of an AIS 0 or AIS 1 injury is modeled. Thus, as before, a positive coefficient means that increasing the value of the explanatory variable tended to decrease injury severity. Results are shown in Table 3. Estimated coefficients that were statistically significant at the 0.05 level are shown in bold.

Table 3. Probit models for the probability of maximum injury severity for head, neck, or face injuries from roof contact being either AIS 0 or 1.

		Unadjusted			
		Intrusion		Post-crash headroom	
		Cont	dich	cont	dich
Intrusion	cont (inches)	-0.055			
	dich		-0.654		
Post-crash headroom	cont (inches)			0.045	
	dich				0.670
Intercept		2.08	2.28	1.81	1.42
% concordant		59.7	29	62	38
c		0.641	0.584	0.637	0.619

		Quarter turn adjusted				Roof exposure adjusted			
		Intrusion		Post-crash headroom		Intrusion		Post-crash headroom	
		cont	dich	cont	dich	cont	dich	cont	dich
Intrusion	cont (inches)	-0.056				-0.052			
	dich		-0.683				-0.592		
Post-crash headroom	cont (inches)			0.050				0.046	
	dich				0.718				0.650
# quarter turns	(end-over-end = 0)	-0.17	-0.17	-0.17	-0.17				
# roof exposures	(end-over-end = 0)					-0.71	-0.71	-0.71	-0.69
End-over-end	(1 = yes / 0 = no)	-1.63	-1.73	-1.62	-1.69	-1.86	-1.94	-1.86	-1.90
Occupant age	(years)	-0.010	-0.007	-0.011	-0.011	-0.011	-0.008	-0.012	-0.011
Occupant sex	(1 = male / 0 = female)	0.08	0.03	0.21	0.16	0.01	-0.02	0.13	0.09
Vehicle	(1 = LTV / 0 = car)	0.25	0.24	0.22	0.28	0.19	0.17	0.16	0.21
Intercept		2.98	3.15	2.69	2.23	3.27	3.39	3.00	2.56
% concordant		64	62.1	63.5	64.6	63.5	61.6	62.9	63.7
c		0.651	0.631	0.646	0.656	0.647	0.63	0.642	0.65

Note: Bolded estimates are statistically significant at the 0.05 level.

Source: NHTSA, NCSA, NASS CDS 1997-2005.

The p-values for all the intrusion and headroom variables were less than 0.0001. The two exceptions were the quarter turn adjusted dichotomous intrusion model, in which the p-value was 0.0005, and the roof exposure adjusted dichotomous intrusion model, in which the p-value was 0.0009. This indicates that, in all cases, the intrusion and headroom variables were statistically significant.

The coefficients on the intrusion variables were negative, indicating that higher intrusion was associated with a higher probability of an AIS 2+ injury. The coefficients on headroom were

positive, indicating that higher post-crash headroom was associated with a lower probability of AIS 2+ injury.

In the eight adjusted models, the number of quarter turns, the number of roof exposures, whether the rollover was end-over-end, and occupant age were statistically significant, whereas occupant sex and vehicle type were not statistically significant. The signs on the coefficients are the same as in the ordered probit analysis. The only exception is that in one of the models, the coefficient on occupant sex is negative.

Ten of the 12 models shown in Table 3 had about the same association between estimated probabilities and observed outcomes. As before, the two exceptions with lower associations were the unadjusted dichotomous intrusion model and the unadjusted dichotomous headroom model.

The coefficients on intrusion and headroom were lower in absolute value in the bilevel models shown in Table 3 than in the multilevel models shown in Table 2. Flannagan et al. (2005) found the same effect when using the AIS 2+ cutpoint in a quarter turn adjusted dichotomous headroom model.

Below is a sample calculation using the unadjusted continuous intrusion model. For the purposes of the example, suppose intrusion was 3 inches. Then, the estimated probabilities are:

$$y = -0.055 * 3 = -0.164$$
$$p(AIS0,1) = \Phi(2.08 + y) = 97.3\%$$
$$p(AIS2+) = 1 - \Phi(2.08 + y) = 2.77\% .$$

Conclusion

This report shows that a statistically significant relationship existed between both vertical roof intrusion and post-crash headroom on the one hand and maximum injury severity of head, neck, or face injury from roof contact on the other hand. The relationship remained regardless of the statistical model used. In particular, the report used both unadjusted and adjusted models, both with continuous and dichotomous versions of the explanatory variables, and with multilevel or bilevel versions of the dependent variable, and still the relationship remained statistically significant.

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DOT HS 810 847
October 2007



U.S. Department
of Transportation
**National Highway
Traffic Safety
Administration**

