

## **INJURY EFFECTS OF ROLLOVERS AND EVENTS SEQUENCE IN SINGLE-VEHICLE CRASHES**

**Kimberly A. Krull**

Department of Civil Engineering, North Carolina State University and  
Highway Safety Research Center, University of North Carolina  
424 Mann Hall, Box 7908, Raleigh, NC 27695-7908  
T: (919) 515-6456  
E: [kknull@eos.ncsu.edu](mailto:kknull@eos.ncsu.edu)

**Asad J. Khattak, Ph.D.**

Department of City and Regional Planning  
3140 New East Building  
University of North Carolina  
Chapel Hill, NC 27599  
T: (919) 962-4760, F: (919) 962-5206  
E: [khattak@email.unc.edu](mailto:khattak@email.unc.edu) W: <http://www.unc.edu/~khattak/res951.htm>

**Forrest M. Council, Ph.D.**

Highway Safety Research Center  
University of North Carolina  
730 Airport Road  
Chapel Hill, NC 27599-3430  
T: (919) 962-2202  
E: [f\\_council@unc.edu](mailto:f_council@unc.edu)

March 2000

**KEYWORDS:** Safety, Crashes, Rollovers, Injury

**WORD COUNT:** Text: 5992 + Tables: 1500 = 7492

---

**Submitted for Publication to:**

**Transportation Research Board  
Washington, D.C.**

INJURY EFFECTS OF ROLLOVERS AND  
EVENTS SEQUENCE IN SINGLE-VEHICLE CRASHES

Kimberly A. Krull

Department of Civil Engineering, North Carolina State University

Asad J. Khattak

Department of City and Regional Planning, University of North Carolina at Chapel Hill

Forrest M. Council

Highway Safety Research Center, University of North Carolina at Chapel Hill

**ABSTRACT**

This study explores the effect of rollovers and tripping event sequence surrounding rollover crashes on driver injury severity. Three year crash and inventory data from Michigan (N=35,447) and Illinois (N=24,296) are analyzed to explore the effect of rollover, while controlling for roadway, vehicle and driver factors. The results show that 9% of single-vehicle crashes are either fatal or cause incapacitating driver injuries (K + A injuries). Significantly more fatalities and incapacitating injuries occur in rollover crashes. Logistic regression models of fatal and incapacitating injuries (K + A) versus other injuries and non-injuries (B + C + O) were estimated separately and together for the two states. The results show that the effects of independent variables are largely consistent across the two states. Driver injury severity increases with rollovers, failure to use a seatbelt, passenger cars (as opposed to pick-up trucks), alcohol use, daylight, rural roads (as opposed to urban), posted speed limit, and dry pavement (as opposed to slick pavement). Restricting the injury models to rollover crashes only, we identified that hitting point objects or longitudinal objects, before rolling over was more severe than rolling over first. The policy implications of the findings for restraint use, crash-testing, and roadside design and hardware are discussed.

## INTRODUCTION

The severity of single-vehicles crashes occurring outside the roadway is a major concern when designing roadsides. When these crashes also involve a rollover, the severity of the crash increases. In 1997, there were 37,280 fatal crashes in the United States, involving 54,000 vehicles. Approximately 10,000 (18.3 percent) of those 54,000 vehicles rolled over. The proportion of rollovers in fatal crashes was almost five times as high as the proportion of rollovers in injury crashes and 14 times as high as the proportion of vehicles involved in property-damage-only crashes that rolled over [Traffic Safety Facts, 1997 (1)]. Viner (2) estimates that rollover crashes cost society between 18.9 and 25.4 billion dollars annually (in 1988 dollars). A better understanding of the nature and severity of rollover crashes in relation to the crash sequence and the vehicle is necessary to provide effective countermeasures.

The purpose of this paper is to understand the aspects of drivers, the roadway, the environment, and the crash experience (rollover or non-rollover) that influence the occurrence of fatal or incapacitating injuries, given that a single-vehicle run off the road crash has occurred. Another purpose of the paper is to understand the sequence of crash-related events that influence the occurrence of fatal or incapacitating injuries once a rollover has occurred. A “sequence of events” variable on a crash report presents the investigating officer’s assessment of event occurring prior to and during the crash event itself, e.g., “ran off road-left, struck bridge abutment, rolled over.” To test hypotheses empirically, the Federal Highway Administration’s Highway Safety Information System (HSIS) database is used for the analyses. The eight-state database contains police crash reports and attributes (driver, vehicle, crash, and environment factors) in combination with roadway inventory data. Michigan and Illinois were selected because the crash reports in both states contain sequence of events data.

## LITERATURE REVIEW

Two studies explored the causes of rollover in run off the road crashes with respect to the roadway environment. Using Illinois crash and roadway data, Viner (3) explored the risk of rollover in ran off the road crashes by land use, road type, and object struck. Hitting fixed objects was the tripping mechanism in one-fourth of ran off road crashes. Slopes were identified as the tripping mechanism in the remaining three-fourths of all rollovers outside the roadway. In a second study, Viner’s (4) efforts concentrated on rollovers that were the result of tripping on sideslopes and ditches by analyzing FARS data and New Mexico crash data. Rollover on slopes and ditches was identified as the leading cause of fatalities in ran off road crashes, with 26% of ran off road rollover fatalities. The first Viner (3) study identified guardrail as the leading fixed object hit with 3.7% of rural and 5.7% of urban rollovers attributed to it. Both studies identified rural ran off road vehicle crashes to be more likely to result in rollover than urban crashes. The first study showed an increase in rollover occurrence with increasing speed limits. It also found no difference in rollover rates for right or left side departures on two-lane roads, but a higher rollover rate for left side (median) departures on interstates.

Bligh and Mak (5) expanded upon this and compared the roadway environment factors to injury rates in rollover crashes by evaluating the severity and frequency of roadside crashes for generic vehicle platforms using FARS, GES, and HSIS data. The study found that crashes involving embankments and rigid fixed objects have the highest

injury rates, crashes involving longitudinal barriers such as guardrail have intermediate injury rates, and crashes involving non-rigid fixed objects have the lowest injury rates.

Four studies compared the risk of rollover crashes by vehicle platform [Viner (3), Viner (4), Bligh and Mak (5), and Viner et al. (6)]. Light trucks were more likely to roll than passenger cars in all four studies. The Bligh and Mak study identified sports utility vehicles specifically in the light truck category as most likely to roll over. Their study found that given a rollover crash, injury rates are higher for passenger cars than for light trucks. The Viner et al. study slightly disagreed. When their study examined rollovers versus non-rollovers in North Carolina data, they found no difference between platforms in fatal and severe injury (K+A) rates, but slightly higher injury rates in passenger cars when compared to a group comprised of pickups, utility vehicles, and vans. However, when comparing FARS data to comparison vehicle registration data and GIS data, there were higher instances of pickup fatalities in fixed object crashes compared to passenger cars. They hypothesized that some of this higher fatality risk may have resulted from ejections in pickup rollovers.

Bligh and Mak explore contributing roadway factors by vehicle type. Rollovers associated with ditches and embankments were similar for both passenger cars and light trucks. However, light trucks were found more likely to roll over in fatal crashes involving utility poles, longitudinal barriers, culverts, and curbs.

Bligh and Mak also examined the sequence of events involved in rollover crashes. The study used Illinois data to identify where rollovers occurred in the sequence of events. The Illinois data reported coding for three events in the impact sequence. However, the first event was usually coded as ran off road, so rollovers in the second event were termed primary and rollovers in the third event were termed secondary. The rollover ratio of primary to secondary rollovers was more than 3 to 1. The fact that no object was mentioned before the rollover in the “primary” category supports the findings of Viner that ditches and embankments were the cause of three-fourths of rollover occurrence.

When viewed together, the relevant research supports that the risk of injury in rollover crashes is a complex relationship between the sequence of events surrounding the rollover, the vehicle type, and the surrounding environment. The Bligh and Mak study starts to bridge the gap between vehicle types, injuries, and the sequence of events in crashes when rollover occurs. However, injury as a function of the sequence of events is not explored. Additionally, vehicle class and sequence of events must be explored further. Some questions remain unanswered: Where in the sequence of events is rolling over the most severe? Does the effect of vehicle platform change when sequence of events is taken into account?

## **METHODOLOGY**

Injury severity in crashes relates to a variety of driver, vehicle, roadway and crash factors. However, the nature of single-vehicle crashes is such that the set of factors affecting severity may be different than for crashes involving multiple vehicles. In multiple vehicle collisions, severity is highly related to the type of collision, collision size/weight of impacting vehicles, points of contact, etc. Injury severity of single-vehicle run off the road crashes is related to what the vehicle experiences outside the roadway and to the shared set of other (e.g., driver) factors. The severity is further complicated

when rollover occurs. Rollover crashes usually occur when vehicles leave the roadway and encounter a tripping mechanism.

This analysis only includes single-vehicle crashes that did not impact another vehicle. The single-vehicle crashes that occur because the vehicle left the roadway or ran off the road are referred to as 'single-vehicle crashes'. Regression models are estimated to identify the set of factors that affect the severity of single-vehicle crashes and those that affect the severity of the subset of these crashes in which a rollover occurs. Additionally the models provide a numeric relationship between the factors and the marginal probability of a fatal or incapacitating injury, given that the single-vehicle crash has occurred.

### **HSIS Crash Data**

The 1994-1996 Michigan crash files and 1993-1995 Illinois crash files from the Federal Highway Administration's Highway Safety Information Systems (HSIS) were used for this analysis. HSIS is a multi-state relational database that contains crash, roadway, and vehicle information. The states in the database are selected based on the quality of data available. The database is separated into individual files that can be linked together. The accident file, vehicle subfile, and roadlog file were linked together and used for analysis individually for each state. The merged files (Michigan and Illinois) contained single-vehicle crashes, both rollover and non-rollover. The only vehicles types analyzed were passenger cars, pickup trucks, and vans. All others (e.g., large trucks and buses) were removed. After the individual analyses were performed, the two states were merged into one large file and reanalyzed.

The crash and vehicle information is taken from police reported crashes. The data are acquired annually by HSIS, processed into a common computer format, documented, and prepared for analysis. There are some inherent problems with police reported crash data. Specifically, the accuracy of the crash data is dependent on the training and expertise of the police officer collecting the information, and the difficulty of collecting the information. Seat belt data, for instance, is problematic because it takes the judgement of a police officer after the collision has occurred, with no visual evidence in most cases. Alcohol indicators are measured with error, but less problematic in that police are trained to detect drinking and routinely engage in DUI (Driving Under the Influence) related patrols. Speed of impact is often not recorded in police crashes, however posted speed limit and functional class are easily obtained surrogates.

### **Modeling**

Logistic regression models were estimated using the statistical software package SPSS (7). The estimation gives the coefficients for the independent variables. Having estimated the coefficients, logistic regression can predict the presence or absence of a characteristic or outcome based on the values of a set of predictor variables. In this analysis, the presence of fatal or incapacitating injuries is the characteristic the logistic regression is predicting. Only driver injury is analyzed. Passenger injury is not included to avoid controlling for vehicle occupancy. For the HSIS data set, independent variables such as road classification or driver gender are categorical, and variables such as driver age are continuous. Categorical independent variables are modeled in relation to a base category.

The KABCO injury scale is used on the Michigan and Illinois police reports. The investigating officer determines the level of injury. The most severe category is ‘fatal’ (K); the next most severe category is ‘incapacitating injury’ (A); the next most severe category is ‘non-incapacitating injury’ (B); and the least severe category is ‘possible injury’ (C). The last category is ‘no injury’ (O). For this analysis, category ‘K’ and category ‘A’ were grouped together to represent severe injuries. The emphasis in the safety community is on K+A collisions. Category ‘B’, ‘C’, and ‘O’ represent non-severe injuries.

Table 1 lists the independent variables considered for the single-vehicle crash model. The expected relationship and the reasoning behind the expectation are stated. Several variables have more than one alternative expected relationship. The independent variables selected were requested from the accident file, vehicle file, or roadway log. Variables were chosen based on theoretical reasoning. A series of models using variable combinations were estimated. The ones that were most parsimonious and had the best statistical properties (e.g., goodness of fit, reasonable parameter magnitudes and t-statistics) are reported as the final models.

The final single-vehicle crash model includes all independent variables listed in Table 1 except for driver gender, ADT, right shoulder width, and left shoulder width. Driver gender is not included for consideration as an independent variable because of corrupt data from the Michigan files. The variable ‘ADT’ is not included because a correlation matrix revealed that it was correlated to the variable ‘Rural functional class’ at the 0.533 level. Correlation over 0.5 can cause multi-collinearity problems. Right shoulder width was correlated to left shoulder width and speed limit at the 0.591 and 0.563 level respectively in the correlation matrix. Therefore, right shoulder width and left shoulder width were excluded. All other variables in Table 1 had acceptable levels of correlation.

Some of the estimated models tested for interactions between variables based on theoretical reasoning. Some of the interactions were of interest per se while others were to control for confounding factors (for a variable to be confounding, it must be related to injury and to the variable that it is interacting with). No statistically significant interactions (10% level) were found in the models, which are not reported in the paper.

It is theoretically possible that during the crash, but before a rollover, the driver is injured, which then accentuates the possibility of a rollover (e.g., a fixed object impact that renders the driver unconscious). If true, then we should use statistical techniques that account for such simultaneity between the rollover and injury variables. However, given the dynamics of single vehicle collisions, we expect that most severe injuries occur during rollover. While there may be situations where prior injuries contribute to rollovers, due to our inability to observe empirical evidence during actual collisions or strong theory to support this bi-directional relationship, estimating simultaneous models is not warranted.

The independent variables for restraint use, vehicle type, and driver age all had large percentages of missing values. Crashes with missing values are typically excluded from the regression. However, such exclusions can be problematic, particularly if a large number of observations are excluded and if the missing variable(s) is systematically related to the dependent variable, e.g., restraint use variable is more likely to be missing for non-injury crashes. To deal with the missing data problems, dummy variables were

created. They allow us to retain some of the data that would otherwise not be used and explore the relationship between missing data and injury severity.

The coefficients of logit model do not provide the marginal effects of the independent variables. That is, one cannot determine the effect on injury of a unit change in an independent variable from the model coefficient alone. In order to compute the marginal change in the probability of a severe injury, it is necessary to convert the estimated coefficients obtained from the logit model into changes in probability. The probability of a fatality or incapacitating injury ( $y=1$ ) is given by:

$$\text{Probability (y=1)} = f(Z) \quad (1)$$

Where,

$$f(x) = (e^x / (1 + e^x))$$

$$Z = \beta \mathbf{x}^t + e \quad (2)$$

And

$\beta$  is a row vector of coefficients,

$\mathbf{x}^t$  is a column vector of variables,

$e$  is the error term,

$f(x)$  is the logistic probability function,

$y$  is a variable taking on the values of one when incapacitating or fatal injury is observed and zero otherwise.

For continuous variables the marginal change in the probability is given by

$$\partial \text{prob}(y=1) / \partial x_i = (\partial f(Z) / \partial Z) (\partial Z / \partial x_i) \quad (3)$$

The change in the logistic function with respect to  $Z$  is

$$\partial f(Z) / \partial Z = (e^Z (1 + e^Z) - e^Z (e^Z)) / (1 + e^Z)^2 \quad (4)$$

$$= (e^Z + e^{2Z} - e^{2Z}) / (1 + e^Z)^2 \quad (5)$$

$$= e^Z / (1 + e^Z)^2 \quad (6)$$

And the change in  $Z$  with respect to a particular  $x_i$  is

$$\partial Z / \partial x_i = \beta_i \quad (7)$$

The marginal change in probability is then given by

$$\partial \text{prob}(y=1) / \partial x_i = \beta_i e^{\beta \mathbf{x}} / (1 + e^{\beta \mathbf{x}})^2 \quad (8)$$

Since the probability is a non-linear function of  $\mathbf{x}$ , it is necessary to find the marginal change in probability at a certain set of  $\mathbf{x}$  variables. The marginal changes are calculated at the means of both the continuous and discrete  $\mathbf{x}$  variables. Interpolation must not go far beyond these means without changing these values to meet the new assumptions.

For computing marginal changes in probability with respect to changes in the discrete variables, the change in probability is computed as the difference in probability between the variables at one and zero. The probability that  $y=1$  is given by

$$\text{Prob}(y=1) = e^{\beta x} / (1 + e^{\beta x}) \quad (9)$$

Thus the change in probability of observing a  $y=1$  from changing  $x_i=0$  to  $x_i=1$  is given by

$$\Delta \text{Prob}(y=1) / \Delta x_i = \text{Prob}(y=1)_{x_i=1} - \text{Prob}(y=1)_{x_i=0} \quad (10)$$

Where  $\text{Prob}(y=1)_{x_i=1}$  is the probability of observing  $y=1$  for  $x_i=1$  and all other variables are at their mean and  $\text{Prob}(y=1)_{x_i=0}$  is the probability of observing a  $y=1$  for  $x_i=0$  and all other variables at their mean. These are the indicator marginal effects.

## FINDINGS

### Overview

The driver injuries are split into a binary variable for incapacitating and fatal driver injuries (K+A) and non-incapacitating driver injuries (B+C+O). The incapacitating and fatal injuries are referred to as severe injuries and the non-incapacitating injuries as non-severe injuries. The resulting distribution between rollover and non-rollover single-vehicle crashes is presented in Table 2 for the Illinois and Michigan samples. The total number of single-vehicle crashes is 59,743 with 35,447 crashes from Michigan and 24,296 crashes from Illinois. The subset of those crashes that involved a rollover is 10,871. Of those 10,871, only 10,571 had relevant sequence of events data for the rollover events sequence models. Of the crashes with relevant sequence of events data, 4,331 crashes were from Illinois and 6,240 were from Michigan.

For both states, 9% of single-vehicle crashes are severe (5,383/59,743). There is variation in severity across the two states, with Illinois single-vehicle crashes being more severe than Michigan crashes. Given somewhat equal speed limits and urban/rural split, it is possible that Michigan reports more non-severe crashes. This can result in proportionally less severe injuries in Michigan. Table 3 presents descriptive statistics for the two states separately and combined.

### Michigan

Seatbelt use had a high percentage of missing data (13%). When the seatbelt use data was present, most drivers (90%) were reported to be wearing their seatbelt. However, this is not always an accurate variable because the drivers report the seatbelt use to the investigating officer after the crash. Observational studies of seatbelt use have consistently indicated that crash reported use is inflated. The investigating officer on the other hand, verifies alcohol use. Fifteen percent of the drivers were under the influence of alcohol. The average driver age was 33 years with a range of 13 to 96 years old.

The largest percentage of the crashes occurred during daylight conditions (48%), 52% occurred during nighttime, dawn, or dusk. The pavement condition was slick for 60% of the crashes and dry for 40% of the crashes. The majority of the crashes occurred on rural roads (54%) but the urban functional class closely followed (46%). The speed

limit ranged from 40.3 km/h (25 mph) to 104.7 km/h (65 mph) with a mean of 89 km/h (55 mph.)

### *Illinois*

Seatbelt use also had a high percentage of missing data for Illinois (14%). When the seatbelt use data were available, most drivers (83%) were reported to be wearing their seatbelt. Slightly more drivers (17%) were under the influence of alcohol compared to Michigan. The average driver age was 32 years.

Slightly fewer crashes occurred during daylight conditions (45%) in Illinois than in Michigan (48%). The real difference between the two states was in the pavement condition. The pavement condition was slick for 40% of the crashes and dry for 60% of the crashes in Illinois. This is opposite of the Michigan distribution. The majority of the crashes occurred on rural roads (55%). The mean speed limit was 83 km/h (52 mph.)

## **Model Results**

The results are presented in two models for both data sets. The first, the single-vehicle crash model, examined factors that affect driver injury severity for all single-vehicle crashes. The examination includes the occurrence or non-occurrence of rollover. The second, the rollover events sequence model, examines how the crash sequence affects injury severity given that a rollover has occurred.

### *Single-vehicle Crash Model*

Table 4 displays the results of the single-vehicle crash model. The table displays the models for Michigan, Illinois, and the two states combined. In the pooled model (where coefficients are restricted to be the same across the two states), an additional independent variable, 'state', was added to account for any differences in injuries between Illinois and Michigan not accounted for by the other variables. The p-values, coefficients, and marginal effects are provided for each independent variable. Independent variables with a p-value below 0.100 significantly affect the occurrence of an incapacitating injury (at the 10% cutoff level). Negative coefficients reduce the probability of severe injuries; positive coefficients increase the probability. The coefficients of each variable were used in the calculation of the marginal effects. The marginal effect of each variable on the probability of severe injury was found by holding the other independent variables at their mean. The marginal effect reported for the continuous variables is the change in the probability of having a severe injury for a unit change (increase) in the continuous variable. The indicator marginal effect reported for discrete variables is the change in the probability of having a severe injury for each category in relation to the base category. Positive marginal effects increase the probability of severe injury, while negative marginal effects decrease the probability of severe injury.

From the likelihood ratio test statistics at 13 degrees of freedom, the hypothesis that all the coefficients are equal to zero can be rejected for the Michigan, Illinois, and pooled models. The informal goodness of fit shows that the pooled (restricted) model achieves the best fit. The Michigan model fit (Rho-squared or McFadden's  $R^2$ ) is relatively better than the Illinois model fit. This informal goodness of fit statistic is based on the log-likelihoods at zero and convergence and it is useful for comparing models.

Based on a chi-squared test of the log likelihoods at convergence for the unrestricted (Michigan and Illinois) models versus the restricted (pooled) model, the unrestricted models better explain the data.

Restraint use has the largest marginal effect on the probability of severe injury, followed by rollover involvement and then slick roadways. In the pooled data set, restraint use decreases the chance of a severe injury by 15.6%. Rollover involvement increases the chance of severe injuries by 7.09%, and slick roadways decrease the chance by 4.02%. This trend is consistent across all three data sets but with varying magnitudes.

The significant independent continuous variables are 'driver age' and 'speed limit'. 'Speed limit' is slightly outside of the target level of significance for the Illinois data but was still included in the model as the posted speed limit is a surrogate for vehicle crash speed. The significant independent categorical variables report rollover involvement, alcohol use, rural vs. urban, restraint use, daytime vs. nighttime, slick vs. dry roadway, and vehicle type.

The categorical independent variable, 'vehicle type', uses the category 'passenger car' as the base. The vehicle category 'vans/motorhome' does not have a significant relationship for the Michigan data indicates that there is no statistically significant difference in severe injuries between vans/motorhomes and passenger cars in Michigan. However, in the Illinois data, vans/motorhomes decrease the probability of severe injuries when compared to passenger cars. Pickup trucks show a decreased probability of severe injuries for all three data sets when compared to passenger cars.

The independent variable 'state' was included in the pooled model to account for differences in the states not accounted for in the other variables. The differences in the two data sets reflected in this variable can be due to systematic differences in coding, differences in crash reporting thresholds (to the best of our knowledge, the Michigan crash reporting limit was \$400 in property damage and the Illinois limit was \$500 in property damage during the time the data were collected), and the incongruent years of data used (1993-1995 for Illinois and 1994-1996 for Michigan).

The missing data dummy variables for driver age and restraint use are significant at the 0.1000 level for all three data sets. This reflects that there was a systematic reason for the missing variables. When driver age or restraint use was missing, severe injury was less likely. A possible explanation for this is that there is less attention to detail by the police officer in less severe crashes and information such as driver age or restraint use was more likely to be omitted from the report form.

#### *Rollover Events Sequence Model*

Michigan and Illinois crash reports contain sequence of events data. There are four possible events in the sequence in the Michigan reports and three in the Illinois reports. However, not all of the sequence of events data is relevant for crash modeling. Possible variables include 'loss of control' and 'other non-collision'. Two investigating police officers could code the same run off the road single-vehicle rollover crash in two completely separate ways. One may code the crash as 'other non-collision', 'loss of control', 'ran off road-left', and 'rollover'. Another officer may code the same crash as 'ran off road-left' and 'rollover'. The rollover in the former scenario might be coded as an event four rollover and the latter coded as an event two rollover. This scenario

exemplifies the problems with identifying the severity of rollover crashes as a function of sequence of events.

In order to mitigate these concerns, the subset of rollover single-vehicle run off the road crashes were re-coded into five categories: 1) rolled over initially after leaving the roadway, 2) left the roadway, hit a point fixed object, and then rolled over, 3) left the roadway, hit a longitudinal object, and then rolled over, 4) left the roadway, hit curb object (including traffic islands), and then rolled over, or 5) left the roadway, hit ditch or embankment, and then rolled over. Crashes in the first category, 'rolled first', may or may not have hit objects after rolling over. Point objects include roadside objects such as bridge ends, traffic signs, signal posts, light supports, utility poles, mailboxes, trees, fire hydrants, impact attenuators, and culverts. Longitudinal objects include bridge rails, guardrail face, guardrail end, and median barrier. Crashes not fitting into one of these five categories were excluded.

Table 5 presents the distribution of severe injuries by sequence of events category. The categories 'hit point object then rolled' and 'hit longitudinal object then rolled' appear to be the most dangerous events sequences when examining the severe injury percentages.

Using the subset of rollover crashes that had a defined sequence of events, a set of models with alternative specifications were estimated. These rollover events sequence models used the independent variables identified by the single-vehicle crash models in addition to the event sequence categories. Table 6 lists the resulting model variables, p-values, and marginal effects for the Michigan, Illinois, and pooled data sets.

From the likelihood ratio test statistics at 16 degrees of freedom, the hypothesis that all the coefficients are equal to zero can be rejected for the Michigan, Illinois, and pooled models. The informal goodness of fit statistic shows that the pooled (restricted) model achieves the best fit. The Michigan model fit is better than the Illinois model fit. Based on a Chi-squared test of the log likelihood at convergence, the separate models are better than the pooled model.

The rollover events sequence categories are reported in relation to the category, 'rolled first'. The variables 'hit point object then rolled' and 'hit longitudinal object then rolled' significantly increase the probability of severe injury in the restricted and unrestricted models. The pooled model marginals indicate that hitting a point object first and then rolling increases the chance of severe injury by 8%, whereas hitting a longitudinal object and then rolling increases the chance by 6%. Although the coefficient of the category 'hit curb object then rolled' is negative in relation to 'rolled first', it is not significant at the 0.100 level for any of the data sets. Therefore, there is no statistically significant difference between rolling over first, or hitting the curb and then rolling over. The category 'hit curb object then rolled' has a relatively small sample size of 100 total.

The vehicle categories are reported in relation to the category 'passenger cars'. The categories 'Pickup Truck' and 'Vans/Motorhomes' are not significant at the 0.100 level for the Michigan data. In the Illinois data, vans/motor homes decrease the probability of severe injury, followed closely by pickup trucks. It must be noted again that the probability of severe injury is reduced in relation to a passenger car given that a single vehicle run off the road rollover has occurred.

## Policy Implications

This study supports earlier findings and presents new information. The analyses reiterated the importance of restraint use in preventing severe injury in single-vehicle crashes and the fact that rollover increases such injury. While we should continue to spend research and implementation funds on roadway and vehicle-related programs to reduce rollovers, the maximum effect on roadside injury is most likely to come from programs which increase restraint use among all drivers (e.g., well-enforced seatbelt usage laws with driver points as penalties).

However, because of the influence of rollover on the probability of severe injury, there is also a policy implication that the roadway and roadside design community must continue to both build forgiving roadsides that do not produce rollover (e.g., clear roadsides, less severe sideslopes). Innovation in finding new designs (e.g., better ditch design, innovative curve treatments to prevent roadside excursions) may further reduce the problem.

In contrast to earlier studies, the vehicle platform effect is not present—i.e., pickup truck and van drivers do not appear to be more severely injured than passenger car drivers in these crashes. In fact, the opposite was indicated for the Illinois and the pooled data models for pickup trucks and vans. That is, pickup truck and van drivers were less likely to be injured compared with passenger car drivers, given that a single vehicle run off the road crash occurred (regardless of rollover). This may be due to the fact that more crash energy (e.g., higher speed) is required to cause a passenger car to overturn. If the passenger car rollover requires more energy, then the results of such a rollover may be more severe in terms of injury. However, with the bottom line being that severe injury levels are approximately equal (lower for pickup trucks and vans in this study), another look at the crash-test issue of heavy pickup trucks in crash tests may be warranted (i.e., in current crash tests, the large pickup is used as a substitute for the heavy passenger car used under earlier test standards). Efforts to mitigate the rollover problem should be directed to all vehicle types and not necessarily on to a given class of vehicles

Finally, the analyses of sequence of events in rollover crashes have provided unique information. It is impossible with police level crash data to separate the injury level sustained from when it occurred. Based on the dynamics of a crash, one would assume that an occupant is more likely to sustain severe injury in a rollover than in the impact with another object (but no rollover). One goal of the research is to determine which was more severe in terms of injury – the crash sequence involving rollover after impacting a fixed object versus the sequence involving a rollover without first impacting a fixed object. The findings indicate that the risk of severe injury is greater if the rollover follows an impact with a point or longitudinal object than when rollover occurs without or before such an impact. Clearly, this does not imply that we should abandon the use of longitudinal barriers to protect dangerous roadsides. Indeed, we expect that this finding is partially due to the nature of the roadside when no point object or barrier is struck. Since each state has a policy of protecting the worst roadsides with longitudinal barriers, then the remaining sections without barriers must, by definition, be less severe than those behind the barriers. Therefore the rollover comparison is not between barriers and all roadsides, but between barriers and the less severe roadsides that remain after barrier protection is in place.

From a policy viewpoint, the findings support the continuing need to design roadside hardware such that rollover harm is minimized. More effort should be concentrated on the development and testing procedures for the elimination of rollovers. The fact that rollover crashes after striking hardware are significantly worse than rollover crashes without or before such impacts implies that there may be room for improvement in the hardware, and that the roadside safety community should continue to develop innovative designs which both minimize the risk of rollover crashes, and perhaps lessen the severity of rollover crashes that occur.

## **CONCLUSION**

This study analyzes the effect of rollovers on driver injury in single-vehicle crashes and explores how injury is influenced by the sequence of events leading to a rollover. The study is limited by the quality of the police reported crash files in regard to missing cases, self-reported variables (i.e., seatbelt use), miscoded variables, and the inherent assumptions of logistic regression. However, we have attempted to control for as many exogenous variables as possible by estimating models with alternative specifications.

The variables that increase the probability of severe injury are rollover involvement, passenger cars (as opposed to pick-up trucks and vans/motorhomes), failure to use a seatbelt, alcohol use, daylight, rural roads (as opposed to urban), higher speed limits, and dry pavement (as opposed to slick pavement). These variables also increase injury severity, given rollovers. Additionally, hitting point objects or longitudinal and then rolling over is more severe than rolling over first. The main policy implications are that there is potential for designing roadside hardware and clear zones that reduce the chances of rollover crashes. Furthermore, states need to continue their efforts to increase restraint use. In terms of vehicle types, rollover prevention efforts need to focus on all vehicle types and not necessarily on any given vehicle class.

Finally, more research is needed on countermeasures such seatbelt usage, better ditch design, and innovative curve treatments that prevent roadside excursions. In-depth research on the effect of specific point and longitudinal objects in rollover crashes may also be beneficial for comparison with non-rollover crashes.

## ACKNOWLEDGEMENTS

The data for this paper were extracted from FHWA's Highway Safety Information System (HSIS). The authors appreciate FHWA's support in providing these data, and the data file development efforts of Ms Carolyn Williams of the HSIS project. Dr. Council's efforts on this paper were partially supported by the HSIS project. However, the opinions, findings, and conclusions or recommendations are those of the authors and do not necessarily reflect the view of the FHWA. The marginal effect derivation and calculations were completed with the assistance of Brad Eccles of the Research Triangle Institute.

## REFERENCES

1. Traffic Safety Facts 1997, US Department of Transportation, National Highway Traffic Safety Administration.
2. John G. Viner. Harmful Events in Crashes. *Accident Analysis and Prevention*, Vol. 25, No. 2, 1993, pp. 139-145.
3. John G. Viner. Risk of Rollover in Ran-Off-Road Crashes. In *Transportation Research Record 1500*, TRB, National Research Council, Washington, D.C. 1995.
4. John G. Viner. Rollovers on Sideslopes and Ditches. *Accident Analysis and Prevention*, Vol. 27, No. 4, 1995, pp. 483-491.
5. Roger P. Bligh and King K. Mak. Crashworthiness of Roadside Features across Vehicle Platforms. In: Transportation Research Board Reprint CD from the 78<sup>th</sup> Annual meeting of the Transportation Research Board, January 1999, Washington, D.C.
6. John C. Viner, Forrest M. Council, and J. Richard Stewart. Frequency and Severity of Crashes Involving Roadside Safety Hardware by Vehicle Type. In *Transportation Research Record 1468*, TRB, National Research Council, Washington, D.C., 1994, pp. 10-18.
7. SPSS for Windows, Rel. 7.5.1. and SPSS Advanced Statistics Guide. Chicago: SPSS Inc.1996.

### **List of Tables**

Table 1: Independent Variables and their Expected Relationships for the Single-vehicle Crash Model

Table 2: Distribution of Illinois and Michigan Driver Severe Injuries for Rollover and Non-Rollover Single-vehicle Crashes

Table 3: Independent Variable Distribution for Michigan, Illinois, and Pooled Data

Table 4: Single-vehicle Crash Model Results of Illinois, Michigan, and Pooled Data

Table 5: Distribution of Injuries for Each Rollover Events Sequence

Table 6: Rollover Events Sequence Model Results for Single-vehicles Rollover Crashes of Illinois, Michigan, and Pooled Data

Table 1: Independent Variables and their Expected Relationships for the Single-vehicle Crash Model

Variable	Reasoning	Expected Relationship
Driver Age	Susceptibility to injury increases with age	Increase in severe injury
Driver Gender	Women are physiologically more susceptible to injury	Increase in severe injury among women
Driver Restraint	Restraints prevent ejection and contact with vehicle interior	Decrease in severe injury with restraint use
Alcohol Involvement	Alcohol use may increase risky driving (e.g. higher speed)	Increase in severe injury with alcohol use
Slick Roadway	Slick roadways reduce braking performance	Increase in severe injury
	Drivers may slow down on slick roads	Decrease in severe injury
Light	Daylight increases visibility	Decrease in severe injury during daylight
	Increased visibility increases speed	Increase in severe injury in daylight
ADT	Increased ADT causes congestion	Decrease in severe injury
Rural functional class (versus urban)	Rural roads are less likely to be congested (i.e. higher speeds)	Increase in severe injury
	Rural roads have more clear zone	Decrease in severe injury
Median width	Increased median width provides some recovery before crashing	Decrease in severe injury
Right Shoulder Width	Wide shoulders may reflect better roadside design	Decrease in severe injury
Left Shoulder Width	Wide shoulders may reflect better roadside design	Decrease in severe injury
Average Lane Width	Wide lanes may reflect better road design	Decrease in severe injury
Speed Limit	Increased speed results in increased crash force	Increase in severe injury
Pick-up Trucks	Large vehicles provides greater protection than cars	Decrease in severe injury
	Pickups overturn more often in off-road crashes	Increase in incapacitating injuries
	Pickup drivers wear seatbelt less often	Increase in incapacitating injuries
Vans	Large vehicles provides greater protection than cars	Decrease in severe injury
Rollover Involvement	Rolling over results in greater energy transfer	Increase in severe injury

Table 2: Distribution of Illinois and Michigan Driver Injuries for Rollover and Non-Rollover Single-vehicle Crashes

Crash Type	Illinois (1993-1995)			Michigan (1994-1996)		
	Severe Injury (K+A)	Non-Severe Injury (B+C+O)	Total	Severe Injury (K+A)	Non-Severe Injury (B+C+O)	Total
Non-Rollover	2059 (10.5%)	17552 (89.5%)	19611 (100%)	1286 (4.5%)	27475 (95.5%)	28761 (100%)
Rollover	1251 (26.7%)	3434 (73.3%)	4685 (100%)	787 (11.8%)	5899 (88.2%)	6686 (100%)
Total	3310	20986	24296	2073	33374	35447

Table 3: Independent Variable Distribution for Michigan, Illinois, and Pooled Data

Variable	Illinois (1993-95)			Michigan (1994-96)			Pooled		
	Mean	Range	S <sub>d</sub>	Mean	Range	S <sub>d</sub>	Mean	Range	S <sub>d</sub>
Alcohol Involvement	.1696	0/1	.3753	.1439	0/1	.3510	.1539	0/1	.3608
Daylight	.4474	0/1	.4972	.4778	0/1	.4995	.4656	0/1	.4988
Driver Age (yrs)	32.20	14-97	14.49	33.59	13-96	13.67	33.03	13-97	14.02
Driver Age Dummy (for missing values)	.0340	0/1	.1811	.1029	0/1	.3038	.0753	0/1	.2638
Rural Functional Class	.5368	0/1	.4987	.5349	0/1	.4988	.5357	0/1	.4987
Posted Speed Limit (km)	83.13	32-105	15.5	89.60	40-105	13.20	87.03	40-105	14.52
Restrained	.7142	0/1	.4518	.7777	0/1	.4158	.7523	0/1	.4317
Restraint Dummy (for missing values)	.1545	0/1	.3614	.1405	0/1	.3475	.1461	0/1	.3532
Rollover	.1928	0/1	.3945	.1865	0/1	.3895	.1890	0/1	.3915
Slick Roadway	.4144	0/1	.4926	.5950	0/1	.4909	.5239	0/1	.4994
Passenger Car Vehicle Type	.7782	0/1	.7383	.8292	0/1	.6646	.8087	0/1	.6964
Van/Motorhome Vehicle Type	.0667	0/1		.0527	0/1		.0583	0/1	
Pickup Truck Vehicle Type	.1551	0/1		.1181	0/1		.1329	0/1	
Vehicle Type Dummy (for missing values)	.0285	0/1	.1663	.1399	0/1	.3469	.0952	0/1	.2638
State (Illinois)	NA	NA	NA	NA	NA	NA	.5991	0/1	.4901

Table 4: Single-vehicle Crash Model Results of Illinois, Michigan, and Pooled Data

Variable	Illinois (1993-95)			Michigan (1994-96)			Pooled		
	Beta	P-value	Margin	Beta	P-value	Margin	Beta	P-value	Margin
Alcohol Involvement	.4761	.0000	0.0465	.4287	.0000	0.00896	.4676	.0000	0.0291
Daylight	.0825	.0729	0.0069	.1371	.0109	0.00248	.1195	.0006	0.0065
Driver Age *	.0112	.0000	0.0009	.0128	.0000	0.00014	.0118	.0000	0.0006
Driver Age Dummy (for missing values)	-2.771	.0000	-0.0821	-1.303	.0000	-0.01246	-1.165	.0000	-0.0426
Rural Functional Class	.2533	.0000	0.0183	.1708	.0010	0.00266	.2114	.0000	0.0113
Posted Speed Limit *	.0025	.1429	0.0002	.0057	.0054	0.00006	.0044	.0007	0.0002
Restrained	-1.652	.0000	-0.2470	-2.044	.0000	-0.10179	-1.829	.0000	-0.1561
Restraint Dummy (for missing values)	-0.6879	.0000	-0.0419	-.6559	.0000	-0.00819	-.6665	.0000	-0.0294
Rollover	.9737	.0000	0.1156	.9862	.0000	0.02760	.9871	.0000	0.0709
Slick Roadway	-.6066	.0000	-0.0381	-.8387	.0000	-0.02170	-.7255	.0000	-0.0402
Vehicle Type (Base Passenger Car)		.0003			.0455	0.00000		.0000	
Van/Motorhome	-.2253	.0109	-0.0165	.0014	.9901	0.00002	-.1401	.0468	-0.0071
Pickup Truck	-.2046	.0006	-0.0151	-.1938	.0135	-0.00299	-.2055	.0000	-0.0103
Vehicle Type Dummy (for missing values)	.6417	.0000	0.0669	-.1240	.0820	-0.00197	.0430	.4694	0.0024
State (Illinois)	NA	NA	NA	NA	NA	0.00000	.7573	.0000	0.0442
Constant	-1.507	.0000	NA	-2.275	.0000	NA	-2.313	.0000	NA
Number of Observations	21,669			34,586			56,255		
-2 Log-likelihood at zero	17,685.341			15,461.324			34,223.505		
-2 Log-likelihood at convergence	15,091.469			12,910.653			28,539.503		
Likelihood Ratio Test Statistic	2,593.872			2,550.671			6102.842		
Degrees of Freedom (DF)	13			13			14		
McFadden's R <sup>2</sup>	.147			.165			.166		

\* Denotes continuous variables with indicator marginal effects

Table 5: Distribution of Injuries for Each Rollover Events Sequence

Event	Illinois (1993-95)			Michigan (1994-96)		
	Severe Injury	Non-severe Injury	Total	Severe Injury	Non-severe injury	Total
Rolled First	671 (24.4%)	2077 (75.6%)	2748 (100%)	491 (9.9%)	4462 (90.1%)	4953 (100%)
Hit point object then rolled	231 (33.9%)	451 (66.1%)	682 (100%)	92 (22.7%)	314 (77.3%)	406 (100%)
Hit longitudinal object then rolled	114 (36.9%)	195 (63.1%)	309 (100%)	54 (21.4%)	198 (78.6%)	252 (100%)
Hit curb object then rolled	12 (21.1%)	45 (78.9%)	57 (100%)	4 (8.2%)	45 (91.8%)	49 (100%)
Hit ditch object then rolled	223 (25.2%)	662 (74.8%)	835 (100%)	89 (12.3%)	635 (88.6%)	724 (100%)
Total	1254	3430	4681	730	5654	6384

Table 6: Rollover Events Sequence Model Results for Single-vehicles Rollover Crashes of Illinois, Michigan, and Pooled Data

Variable	Illinois (1993-95)			Michigan (1994-96)			Pooled		
	Beta	P-value	Margin	Beta	P-value	Margin	Beta	P-value	Margin
Alcohol Involvement	.6253	.0000	0.1226	.2674	.0173	0.0202	.4861	.0000	0.0655
Daylight	.2689	.0010	0.0487	.2173	.0232	0.0153	.2698	.0000	0.0329
Driver Age	.0112	.0001	0.0020	.0171	.0000	0.0012	.0138	.0000	0.0017
Driver Age Dummy	-3.240	.0010	-0.2320	-.9253	.0000	-0.0482	-1.104	.0000	-0.0900
Rural Functional Class	.2070	.0384	0.0362	.1733	.0738	0.0118	.1786	.0095	0.0210
Posted Speed Limit	.0093	.0115	0.0017	.0111	.0180	0.0008	.0098	.0006	0.0012
Restrained	-1.486	.0000	-0.3001	-1.878	.0000	-0.2027	-1.668	.0000	-0.2617
Restraint Dummy	-.4852	.0001	-0.0791	-.6722	.0002	-0.0386	-.5216	.0000	-0.0551
Slick Roadway	-.6648	.0000	-0.1123	-1.030	.0000	-0.0794	-.8460	.0000	-0.1020
Vehicle Type (Base Category Passenger Car)		.0066			.4606			.0061	
Van/Motorhome	-.3275	.0152	-0.0549	-.0228	.9012	-0.0016	-.2294	.0360	-0.0259
Pickup Truck	-.2378	.0146	-0.0413	-.1622	.2134	-0.0108	-.2128	.0066	-0.0247
Vehicle Type Dummy	.4608	.0156	0.0920	-.1582	.1793	-0.0106	-.0073	.9400	-0.0009
Sequence of events (Base category Rolled First)		.0002			.0000			.0000	
Hit point object then rolled	.3673	.0005	0.0706	.7176	.0000	0.06575	.4811	.0000	0.0668
Hit longitudinal object then rolled	.5260	.0003	0.1056	.6732	.0002	0.06142	.5754	.0000	0.0834
Hit curb object then rolled	.0227	.9497	0.0041	-.4580	.4067	-0.0265	-.1507	.6123	-0.0173
Hit ditch object then rolled	.1177	.2452	0.0216	.2271	.0906	0.0172	.1626	.0436	0.0205
State (Illinois)	NA	NA		NA	NA		.7590	.0000	0.0976
Constant	-1.449	.0000		-2.219	.0000		-2.146	.0000	
Number of Observations	4,331			6,240			10,571		
-2 Log-likelihood at zero	5,061.373			4,463.187			9,939.525		
-2 Log-likelihood at convergence	4,411.592			3,757.848			8,216.690		
Likelihood Ratio Test Statistic	649.781			705.339			1722.835		
Degrees of Freedom (DF)	16			16			17		
McFadden's R <sup>2</sup>	.128			.158			.173		