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RISK FACTORS IN LARGE TRUCK ROLLOVERS AND INJURY SEVERITY: ANALYSIS OF SINGLE-VEHICLE COLLISIONS

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Risk factors in Large Truck Rollovers and Injury Severity: Analysis of Single-Vehicle Collisions

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ABSTRACT--Society pays a cost for truck crashes in terms of operational disruptions, injuries and loss of life. Among the 700 large-truck occupant fatalities that occur every year in the US, about 400 occur in single-vehicle truck crashes and many involve rollovers. This study attempts to understand how truck driver behaviors, vehicle factors and crash events influence large-truck rollovers and occupant injuries in single-vehicle crashes. A relatively clean crash and inventory database, named HSIS (Highway Safety Information System) is used for crash analysis. The data come from police-reported crashes in North Carolina during 1996-1998. Over this three-year period, truck rollovers occurred in almost 30% of the 5,163 single-vehicle truck crashes. Rollover propensity is investigated using binary probit models, and injury severity, measured on the KABCO scale (from fatal, severe, moderate, minor to no injury) is examined using ordered probit models. The results are combined using path analysis. New insights emerge about the direct and indirect effects of high-risk factors. The results show that higher risk factors in single-vehicle truck crashes include:

1) Dangerous truck-driver behaviors, particularly speeding, reckless driving, alcohol and drug use, non-use of restraints, and traffic control violations.

2) Truck exposure to roadways that have dangerous geometry, particularly more curves.

3) Trucks that transport hazardous materials and post-crash fires.

Through a combination of countermeasure strategies, we must attempt to reduce these high-risk factors.

INTRODUCTION

Truck rollovers and the resulting safety problems have serious consequences for the traveling public, trucking companies, and truck drivers. For the traveling public, a rolled over semi tractor-trailer can cause traffic congestion and disruptions in supply of certain goods; hazardous truck cargo can be dangerous to humans and the environment, if spilled. For the trucking companies and truck owner-operators, crashes entail delivery disruption, uncertainty and higher overall transportation costs. For truck drivers, crashes represent an occupational hazard. A significant number of truck drivers die from injuries in roadway crashes. Specifically, there were 702 large-truck occupant deaths in roadway crashes in the US during 1998, of which about 90% were truck-drivers. A majority of the truck-occupants who died in crashes were riding tractor-trailers (498 in 1998) and about two-thirds occurred in single-vehicle crashes (Insurance Institute for Highway Safety, 1998). Therefore, this study focuses on analyzing single-vehicle truck crashes.

Owing to their performance, size, maneuverability, design and higher center of gravity trucks have a high rollover propensity with many truck rollovers resulting from the vehicle leaving the roadway and tripping. In response to the need to understand the behavioral and vehicle factors associated with such large truck rollovers in real-life situations, this study applies rigorous statistical methods to analyze North Carolina HSIS (Highway Safety Information System) data from 1996 to 1998. HSIS is a relatively high-quality crash and road inventory database that is federally maintained. North Carolina data are used specifically because there are many truck routes within the state and there are a variety of roadway designs, terrain and weather, exposing trucks to a diverse set of conditions. The key research questions to be addressed in this research are:

- What behavioral, vehicle and roadway factors increase the propensity of single-vehicle truck rollovers?
- How do rollovers impact the severity of injuries to truck occupants?

LITERATURE AND HYPOTHESES

Studies that examine large truck crashes have focused on accident involvement rates for different truck configurations (e.g. Singles vs. Doubles), highway geometric designs, and driver characteristics such as age (1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13). However, previous research focuses on crash occurrence rather than injury severity. Lyman and Braver (14) report that since 1975 the decline in single-vehicle fatal truck crashes per truck VMT was 68%. While this is encouraging, truck drivers are still at a higher risk of dying relative to others in the workforce. Although some studies have explored the role of causal factors in truck-related crashes, few of them have concentrated on the severity of accidents involving trucks (14, 15, 16, 17, 18, 19, 20), and no recent ones have rigorously examined the causes of rollovers and occupant injuries for large trucks. Given the lack of knowledge regarding single-vehicle large truck crashes and rollovers, we hypothesized the effects of several driver, vehicle and roadway factors on truck rollovers and injury severity. Our hypotheses were informed by the empirical evidence reported in previous studies.

The issue of truck crash injury severity is complicated for several reasons (21). Large trucks are particularly prone to rollovers, and rollovers in turn are typically associated with higher injury severity. Additionally, Golob et al. (22) found that the most severe crashes in terms of fatalities were hit-object collisions, these being mostly single-vehicle crashes. Within large trucks, the occupational hazards faced by those driving single-unit trucks versus combination vehicles can perhaps vary. On the one hand, combination trucks might be less maneuverable in crash situations and therefore, more likely to roll over and cause more severe occupant injuries. On the other hand, larger combination vehicles may provide greater occupant protection in crash situations (due to their larger mass) and drivers of combination trucks may compensate for their lack of maneuverability by driving more carefully. Rollovers may have an intervening effect on injury severity.

Tessmer (23) found that there were more fatalities in rural areas than urban areas, and these crashes also involved more trucks. He also found that vehicle rollovers and head-on collisions were more frequent on rural roads (rollovers and head-on collisions were also more severe and trucks were over-represented in such collisions).

A relatively common problem with trucks is their performance. Poor truck performance can be caused by defective equipment, in particular defective truck brakes, which can lead to more severe injuries during collisions. In fact, Jones and Stein (24) found that brake defects were quite common and were found in 56% of the tractor-trailers involved in crashes. Among other truck factors, vehicle age and manufacturer might have a different effect on rollovers and injuries.

Another set of risk factors relate to the truck driver. Dangerous driver behaviors such as speeding, reckless driving and driving under the influence of alcohol, as well as fatigue and sleep deprivation can significantly increase the risk of a severe crash. For example, fatigued and sleepy drivers are less likely to take last second evasive actions to avoid a collision and given a collision mitigate its' severity. Braver et al. (25) found that fatigue and long driving hours have been implicated as risk factors in truck crashes. They reported that almost three-fourths of truck drivers surveyed violated hours-of-service rules. A primary impetus for violating rules appeared to be economic factors (e.g. tight delivery schedules and low payment rates), as well as driver, job, and vehicle characteristics.

Rodriguez et al. (26, 27) explore the role that driver compensation and work conditions play in influencing driver safety outcomes and found that occupational and labor market factors, such as pay, tenure at the job, and percent of miles driven during winter months, are associated with higher crash frequency. Higher pay rates were related to lower expected crash counts for drivers and to a higher probability of having no crashes at all.

Speeding (and higher striking speed) is expected to result in more forceful impacts and therefore more severe injuries to the occupants. Though truck occupants are increasingly using restraints, they are often inconvenient and uncomfortable on long trips. Clearly, the lack of restraint use is likely to increase the risk of injuries in a collision.

Transportation of hazardous materials including gasoline, diesel and fuel oil shipments can complicate the work environment for truck drivers and possibly increase their injury risk during collisions, e.g., due to post-crash fires (Figure 1 shows post-crash fire and rollover crash situations). The risk of severe truck crashes can also increase due to longer stopping distances, particularly in wet and slippery road conditions when the ability to control large trucks deteriorates significantly. However, truck drivers might over-compensate by driving slowly and carefully or they might under-compensate for wet road surfaces. Another risk factor is likely to be darkness. Rollovers and more severe injuries may occur in darkness because it inhibits a driver's visibility, allowing less time for last second maneuvering and braking before tripping/impact. Indeed, Cate and Richards (28) found that rollover crashes in Tennessee were most common during the overnight hours, suggesting that these crashes may be related to driver fatigue and diminished sight distances. Improving roadway lighting may help mitigate the effects of darkness on these crashes.

Within roadway factors, heavy trucks might be harder to control on grades and curves, largely due to their speed and inertia. Golob and Recker (22) found that truck-involved collisions increase under wet and icy or slippery road surface conditions. Similarly, Braver et al. (16) found slippery roads, curves, and hillsides were specific conditions in which fatal crashes were more likely to occur. Cate and Richards (28) found that the greatest rollover risk was posed by curves producing readings of five degrees or more. Therefore, rollovers and injuries may be more likely to occur on curves and grades. Additionally, the recent increases in speed limits, if associated with higher actual speeds, can limit a driver's ability to slow down to reduce the force of impact. Therefore, more rollovers and severe injuries are expected on roadways that allow higher speeds, all else being equal.

Finally, certain combinations of factors (interactions) might be associated with higher injury severity. For instance, crashes that occur on curves and result in rollovers may be more severe; or truck rollovers where post-crash fires occurred may be more severe.

DATA

The 1996-1998 North Carolina HSIS database contains information on over 400,000 crashes and over 700,000 vehicles involved in these crashes (Figure 2). During this three-year period, rollovers occurred in 1,503 (almost 30%) of the 5,163 single-vehicle truck crashes. A majority of the HSIS data required recoding in order to isolate relevant factors for this analysis. For example, the vehicle make HSIS variable was recoded into different indicator variables for each large truck manufacturer, such as Chevrolet, International, Mack, and Toyota. Vehicle year was also recoded into pre-1992 (1) and post-1991 (0) partly because about half of the vehicles in the data set were manufactured pre-1992. HSIS classifies injury severity into five different categories according to Killed (4), Severely Injured (3), Moderately Injured (2), Minor injury (1), and No injury (0).

MODELING

From the methodological standpoint, various disaggregate analysis techniques have been used on understanding the risk factors that increase the probability of injury severity in crashes. These techniques include logistic regression (29, 30, 31), ordered logit and probit models (32), multinomial logit models (33), and nested logit models (34).

For this paper we first examined descriptive statistics (frequency analysis, means, and variances) and explored relationships in the data using cross-tabulations. Then multivariate statistical techniques were used to examine the effects of several factors individually and jointly and account for inter-dependencies among explanatory variables. Binary probit models were estimated to analyze rollover propensity and ordered models to estimate injury severity given a crash. The two-stage modeling process was evaluated under a path analysis approach in order to test rollover propensity as an intervening effect on injury severity.

To model injury severity, ordered probability models are appropriate. The advantage of ordered probability models is that they can capture the qualitative differences between different injury categories, e.g., the effect of a particular variable such as truck type or year of manufacture on the likelihood of a fatality, differently from its influence on the likelihood of a minor or incapacitating injury (15, 32). For the injury severity model, the most severe injured occupant in the accident was used in the analysis. Ordered probability models use a latent variable Y_i^*, which is assumed to be linearly related to the observed $\mathbf{X}_j$ through the structural model:

$$Y_i^* = \boldsymbol{\gamma}_{ij}\mathbf{X}_j + \zeta_i \qquad [1]$$

Where the latent variable Y_i^*, ranging from -∞ to ∞, is mapped to an observed variable Y_i. $\boldsymbol{\gamma}_{ij}$ are the estimated parameters, $\mathbf{X}_j$ is a row vector of risk factors or explanatory variables, and ζ_i is a normal-distributed error term (for probit models). The Y_i variable is our dependent variable (injury severity) coded as 0, 1, 2, 3, 4, being 4 equal to Killed and 0 equal to No Injury.

The idea of a latent variable is that there is an underlying propensity to get injured that generates the observed state. While we cannot directly observe Y_i^*, at some point a change in Y_i^* results in a change in what we observe, namely, whether the people involved in the crash were more severely injured. Therefore, the variable Y_i is thought of as providing incomplete information about an underlying Y_i^* according to the measurement equation (35):

$$Y_i = m \quad \text{if} \quad \mu_{m-1} \le Y_i^* \le \mu_m \qquad [2]$$

Where *m* are the ordinal categories for injury severity, and the *μ*'s are called thresholds or cutpoints.

Given the hypothesized relationship between rollovers and injury severity, we used structural equation models in order to capture potential indirect effects from the independent variables on injury severity via the rollover variable (Figure 3). We specified a recursive model based on our expectations that in most of the crashes, rollover has a causal effect on injury severity. While this is plausible, it can be hypothesized that injury severity causes rollovers, e.g. if the driver first get injured after the vehicle striking an object and then, because the severity of this injury, loses control of the vehicle and rolls over. Although this non-recursive part of the conceptual structure (injury severity causing rollover) may exist, it is not possible to capture data on injury severity just before a rollover. Therefore, the model presented in Figure 3 is identified by the recursive rule and can be estimated using a two-step approach with standard multivariate regression software. Path analysis structure facilitates exploration of direct and indirect effects described by the following equations:

$$Y_1 = \boldsymbol{\gamma}_{\mathbf{11}}\mathbf{X}_{\mathbf{1}} + \boldsymbol{\gamma}_{\mathbf{12}}\mathbf{X}_{\mathbf{2}} + \ldots\ldots + \boldsymbol{\gamma}_{\mathbf{15}}\mathbf{X}_5 + \zeta_1$$
$$Y_2^* = \boldsymbol{\gamma}_{\mathbf{21}}\mathbf{X}_{\mathbf{1}} + \boldsymbol{\gamma}_{\mathbf{22}}\mathbf{X}_{\mathbf{2}} + \ldots\ldots + \boldsymbol{\gamma}_{\mathbf{26}}\mathbf{X}_6 + \beta_{21}Y_1 + \zeta_2 \qquad [3]$$

Where Y_1 denotes whether or not a vehicle rolled over; Y_2^* denotes injury severity; $\boldsymbol{\gamma}_{ij}$ are vectors of estimated parameters for each set of variables $\mathbf{X}_j$; β_{21} is the effect of rollover on injury severity; and ζ's are the error terms, assumed to be uncorrelated.

The measure of goodness of fit estimated for the models is the pseudo-R^2 suggested by McFadden (1973) known also as the "likelihood ratio index", and adjusted by the number of parameters in the model (36):

$$\overline{R}^2_{McF} = 1 - \frac{\ln \hat{L}(M_\beta) - K}{\ln \hat{L}(M_0)} \qquad (4)$$

Where $\ln \hat{L}(M_\beta)$ is the log-likelihood at convergence and $\ln \hat{L}(M_0)$ is the log-likelihood computed without regressors. The advantage of this measure is that it can be interpreted similarly as the linear regression model bounded by 0 and 1; as the model fit improves, Pseudo-R^2 increases (37).

Finally, computation of marginal effects is particularly meaningful for the ordered probit model because the effect of variables $\mathbf{X}_j$ and Y_1 on the intermediate categories is ambiguous if only the parameter estimates are available.

RESULTS

Over the three-year period, truck rollovers occurred in nearly 30% of the 5,163 single-vehicle truck crashes. Though most crashes resulted in no injuries to the truck occupants (64.7%), 0.7% crashes turned out to be fatal, 3.9% involved severe injuries, 13.2% moderate injuries, and 17.2% involved minor injuries. Rollovers were more likely to result in injury, as expected. In fact, 58% of all fatal and 62% of all severe crashes involved a rollover. Single-unit trucks were involved in 47% of the crashes and the rest were combination vehicles. About 22.5% of the involved trucks were longer than 45 feet and 52% were pre-1992 models. Only 13% of all Dodge trucks and 16% of all Toyota trucks rolled over, but 36% of all Peterbilt trucks involved in multi-vehicle collisions rolled over. Though rare, alcohol and drugs were present in about 2% of the crashes. Thirty-five percent of the 118 single-vehicle crashes involving alcohol were rollovers, compared to 29% of single-vehicle crashes not involving alcohol. Speeding was a factor in 1,555 (30%) of the single-vehicle crashes—7% of these crashes resulted in fatal or severe injuries compared to 4% of the non-speeding crashes that resulted in fatal or severe injuries.

Large Truck Rollovers in Single-Vehicle Crashes

In the following sections, we focus on discussing the model results for statistically significant factors at the customary 95% confidence level, although the 90% confidence level is considered to be marginally significant. A positive sign in the models implies higher propensity of rollovers or injuries. Table 1 shows the binary probit model, which is statistically significant and has a reasonably good overall fit (pseudo-R^2= 0.2233). Among vehicle factors, trucks with longer trailers (greater than 45 feet) were more likely to roll over, given a crash. Surprisingly, post-1992 manufactured trucks were significantly more likely to roll over than those manufactured pre-1992. This raises concern about relatively newer model year trucks, requiring further investigation. Though many vehicle makes were included in the model, only trucks produced by Dodge and Toyota were slightly less likely (at the 90% confidence level) to roll over, while those made by Peterbilt were slightly more likely to be involved in rollovers (90% level). No statistical association was found between 1) defective truck brakes and rollovers and 2) single-unit trucks versus combination vehicles and rollover propensity.

Importantly, dangerous driving behaviors that were associated with higher rollover propensity included truck drivers cited with reckless driving, speeding (i.e., violating the speed limit or exceeding the safe speed), passing violation (i.e., passing a school bus or vehicles on a hill or curve), and alcohol/drugs. As indicated by the magnitude of the marginal effects, reckless driving has the largest influence on increasing rollover propensity.

If a truck was making a right, left or a U-turn, then the possibility of a rollover increased significantly. Driving maneuvers that are perhaps not accommodated easily by standard roadway designs can increase the rollover propensity in crash situations. It will be valuable if this risk factor can be communicated to truck drivers.

Crashes that occurred on curves were significantly more likely to involve rollovers. Approximately 43% (503 of 1176) of curve-related crashes were rollovers, while 25% (999 of 3973) of straight roadway crashes were rollovers. Clearly curves represent a rollover hazard for large trucks, although grades were not problematic in single-vehicle truck crashes. Posting signs at sharp curves to warn truck drivers of increasing rollover propensity is one way to communicate the higher risk that curves pose to trucks. Crossing a median is associated with higher rollover propensity. On the other hand, slippery road surfaces are associated with lower truck rollover propensity, perhaps due to slower and more cautious driving on slippery surfaces. Similarly, striking a tree, pole, guardrail or barrier was not as dangerous in terms of rolling over as striking other objects.

The marginal effects presented in Table 1 indicate that relatively large reductions in rollover propensity can be achieved by reducing dangerous driving behaviors; in particular reckless driving, speeding and passing violations, and alcohol/drug use. Indeed, the marginal effects for the later variables indicate that when alcohol or drugs were involved the chance of roll over was about 11% higher. Similarly, speeding and passing improperly increased the chance of roll over by about 17% and 21%, respectively. In this regard, truck driver education and enforcement are two obvious strategies that need to be investigated. Furthermore, counter-measures that can facilitate turning maneuvers for large trucks or at least warn drivers about higher rollover risks need further investigation. Preventing median crossovers and communicating with truck drivers about dangerous curves can perhaps reduce rollover propensity and require further study.

Injury Severity in Single-Truck Crashes

Table 2 presents the ordered probit model that is statistically significant and reflects a reasonably good overall fit (pseudo-R^2= 0.1350). Injury severity among all occupants in single-vehicle truck crashes was significantly higher when a rollover occurred, as expected. The marginal effects of the ordered probit model, presented in Table 3 are interesting to note. In rollover crashes the chances of injuries are higher by 26%, i.e., the chances of minor injuries are 11% higher, moderate injuries are 12% higher, severe injuries are about 3% higher and there is a relatively small increase of 0.35% in the chances of fatalities. Thus, reducing rollover propensity will clearly reduce truck driver injury severity. As expected, with more truck occupants, injuries are more severe, perhaps due to the higher number of people exposed to crash conditions, although this relationship may also reflect the distractions that the truck drivers may experience due to the presence of others.

While Nissan trucks were associated with slightly higher injury severity, the vehicle make variables were mostly non-significant. Defective truck brakes were marginally significant (90% confidence level) and associated with higher truck-occupant injury severity. However, vehicle type (single-unit or combination) was not statistically significant in terms of injury severity.

Dangerous driving behaviors are significantly associated with higher injury severity. Consistent with other safety research, speeding, alcohol/drug use and non-use of restraints significantly increases truck occupant injury severity. Further, injury severity in a crash was significantly higher when the truck driver violated a traffic control sign or signal. The marginal effects indicate that when alcohol or drugs were involved the chance of severe injuries or fatality was about 3% higher and the chance of no injury was 20% lower. Similarly, not wearing seatbelts increased the chance of injury by about 17%. Note that some of the dangerous driving behaviors have a direct effect on injury severity as quantified in this model, and they also increase rollover propensity, indirectly increasing injury severity.

The occupants of trucks that were carrying hazardous materials were likely to receive more severe injuries, on average. This could be due to the dangerous nature of the cargo and/or circumstances. Separately, post-crash fires also increased injury severity. The marginal effects show that the presence of hazardous materials is associated with increased chances of injuries by about 16%; when there is a post-crash fire, the chances of injuries are higher by 20%. The only significant interaction (90% level) was that between post-crash fire and a rollover, indicating that rollovers and fires are a particularly dangerous combination, as one would expect.

Path Analysis Integrating Rollover and Injury Severity Results

Path analysis allows us to jointly analyze the results. When the rollover results are analyzed in conjunction with injury severity results, new insights emerge. Among roadway factors, curves are related to higher injury severity. They increase the chances of truck occupant injury by about 4%, all else being equal. In addition, they have significant indirect effects on injuries through rollovers (as do some other variables including reckless driving, speeding violations and alcohol presence). Specifically, curves increase the rollover propensity by about 9%, as shown by the marginal effect of curves in Table 1. Additionally, rollovers increase the chance of truck occupant injury by about 26% as shown by the marginal effect of rollover in Table 3. So the indirect effect of curves via rollovers is to increase the chances of injury by 2.4% (= 0.0920 * 0.2608 * 100). The total effect of curves on injuries is then 6.4% (4% +2.4%). Likewise, reckless driving increases rollover propensity by about 19%, so the indirect effect of reckless driving via rollovers is to increase injury by 5%. Clearly reducing dangerous driving behaviors can have dual benefits: Reducing rollovers and indirectly reducing injury severity as well as directly reducing truck-occupant injury severity.

CONCLUSIONS

This paper contributes valuable information about the effect high-risk behavioral, vehicle and roadway factors on single-vehicle truck rollovers and occupant injury severity. A key contribution of the research is quantifying the direct and indirect effects of key risk factors on rollovers and occupational injuries sustained by truck occupants, mostly truck drivers. The study demonstrates that truck occupant injury severity can be analyzed more completely when rollovers are considered. The study views rollovers and injuries as separate yet structurally related phenomena. Interestingly, the study finds that higher rollover propensity is associated with curves and dangerous driving behaviors (in particular reckless driving, speeding and passing violations, and alcohol/drug use), these factors also directly increase injury severity.

While the Federal Motor Carrier Safety Administration (FMCSA) has instituted safety programs dealing with truck brakes, alcohol/drugs, hazardous materials, and speed management, this study points to additional programs that might be needed (not only at the federal level, but also at the state and private sector levels). First, rollover reduction programs are needed to promote countermeasure strategies that reduce rollovers by reducing reckless driving, problematic truck turning, and risky behavior on roadway curves. Second, an injury reduction program is needed to promote strategies for reducing the risk of injury to truck occupants, focusing on dangerous driving behaviors, particularly traffic control violations; speeding; alcohol and drug use; non-use of restraints; post-crash fires; and roadway features, especially curves.

Private-sector trucking firms can institute similar rollover and injury reduction programs. For example, they may contribute to rollover and injury reduction through disincentives and incentives (reflected in pay) to reduce dangerous driving behaviors and by providing drivers with greater knowledge about how to negotiate difficult turning maneuvers and informing/educating them about the higher rollover propensity of longer trucks. Perhaps through various compensation schemes, they can target driver alcohol use and other dangerous driving violations (especially speeding, reckless driving and dangerous passing maneuvers) to reduce rollover risk. Firms should encourage restraint use and reduce truck exposure to curvy roads. Ultimately, the public and private sector stakeholders must collaborate on finding comprehensive and integrated countermeasure strategies that cover both truck rollover reduction and injury mitigation. Typical countermeasure strategies for crashes include technology, engineering, education, enforcement, encouragement and exposure reduction to dangerous roads. This study hints at where we might see greater reductions in risks, although the extent to which specific strategies can reduce truck rollover and injury risk needs investigation.

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REFERENCES

1. Polus, A., Mahalel, D., 1985. “Truck impact on roadway safety.” *Transportation Research Record* 1047, pp. 65–71.
2. Chirachavala, T., Cleveland, D., 1985. “Causal analysis of accident involvements of the nation’s large trucks and combination vehicles.” *Transportation Research Record* 1047, pp. 56–63.
3. Carsten, O., 1987. “Safety implications of truck configuration.” *Transportation Research Record* 1111, pp. 17–26.
4. Stein, H.S., Jones, I.S., 1988. “Crash involvement of large trucks by configuration: A case-control study.” *American Journal of Public Health*, Vol. 78, pp. 491–498.
5. Jovanis, P., Chang, H., Zabaneh, I., 1989. “Comparison of accident rates for two truck configurations.” *Transportation Research Record* 1249, pp. 18–29.
6. Jovanis, P., Delleur, J., 1983. “Exposure-based analysis of motor vehicle accidents.” *Transportation Research Record* 910, pp. 1–7.
7. Miaou, S.P., 1994. “The relationship between truck accidents and geometric design of road sections: Poisson versus negative binomial regressions.” *Accident Analysis and Prevention*, Vol. 26 (4), pp. 471–482.
8. Blower, D, Compbell, K., Green, P., 1993. “Accident rates for heavy truck–tractors in Michigan.” *Accident Analysis and Prevention*, Vol. 25 (3), pp. 307–321.
9. Braver, E., Zador, P., Thum, D., Mitter, E., Baum, H., Vilardo, F., 1997. “Tractor-trailer crashes in Indiana: a case-control study of the role of truck configuration.” *Accident Analysis and Prevention*, Vol. 29 (1), pp. 79–96.
10. Saccomanno, F., Buyco, C., 1988. “Generalized Loglinear Models of Truck Accident Rates.” *Transportation Research Record* 1172, pp. 23–31.
11. Joshua, S., Garber, N., 1990. “Estimating Truck Accident Rate and Involvements Using Linear and Poisson Regression Model.” *Transportation Planning and Technology*, Vol. 15, pp. 41–58.
12. Khasnabis, S., Lyoo, S.H., 1989. “Use of Time Series Analysis to Forecast Truck Accidents.” *Transportation Research Record* 1249, pp. 30–36.
13. Campbell, K., 1991. “Fatal Accident Involvement Rates by Driver Age for Large Trucks.” *Accident Analysis and Prevention*, Vol. 23 (4), pp. 287–295.
14. Lyman, S. Braver, E., 2002. “Occupant deaths in large truck crashes in the United States: 25 years of experience.” *Accident Analysis and Prevention* 887, In Press, pp. 1–9.
15. Duncan C., Khattak, A., Council, F., 1998. "Using the ordered probit model to analyze factors that influence injury severity in truck-passenger car rear-end collisions on divided highways." *Transportation Research Record* 1635, pp. 63-71.
16. Braver, E. R., Preusser, C. W., Williams, A. F., Weinstein, H. B., 1996. “Major Types of Fatal Crashes Between Large Trucks and Cars,” IIHS, Arlington, VA.
17. Golob, T., and Recker, W., 1987 “An Analysis of Truck-Involved Freeway Accidents Using Log-linear Modeling.” *Journal of Safety Research*, Vol. 18, pp. 121-136.
18. Alassar, L., 1988. “Analysis of Heavy Truck Accident Severity.” *Journal of Advance Transportation*. Vol. 22, pp. 77-91.

19. Chirachavala, T., Cleveland, D., Kostyniuk. 1984. "Severity of Large Truck and Combination-Vehicle Accidents in Over-The-Road Service: A Discrete Multivariate Analysis. *Transportation Research Record* 975, pp. 23–36.
20. Chang, L., Mannering, F., 1999. "Analysis of Injury Severity and Vehicle Occupancy in Truck- and Non-Truck-Involved Accidents." *Accident Analysis and Prevention,* Vol. 31, pp. 579–592.
21. Proceedings of the Large Truck and Bus Safety Conferences, University of Tennessee, Knoxville, 1997, 1999, 2002.
22. Golob, T., Recker, W., Leonard, J., 1987. "An Analysis of the Severity and Incident Duration of Truck-Involved Freeway Accidents." *Accident Analysis and Prevention*, Vol. 19 (5), pp. 375-396.
23. Tessmer, J. M., 1996. "Rural and Urban Crashes: A Comparative Analysis," National Center for Statistics and Analysis, Washington, D.C.
24. Jones, I., Stein, H., 1989. "Defective equipment and tractor-trailer crash involvement." *Accident Analysis and Prevention*, Vol. 21, pp. 469-81.
25. Braver, E. R., Preusser, C. W., Preusser, D. F., Baum, H. M., Beilock, R., Ulmer, R., 1992. "Long Hours and Fatigue: A Survey of Tractor-Trailer Drivers." *Journal of Public Health Policy*, Volume 13 (3), pp. 341-366.
26. Rodriguez, D. A., Rocha, M., Khattak, A., Belzer, H. M., 2002. "The Effect of Truck Driver Wages and Working Condition on Highway Safety: A Case Study," Paper accepted for presentation at the TRB Annual Meeting, Transportation Research Board, Washington, D.C., 2003.
27. Rodriguez, D. A., Targa, F., Belzer, H. M., 2002. "Pay Incentives and Truck Driver Safety: A Case Study," Paper accepted for presentation at the TRB Annual Meeting, Transportation Research Board, Washington, D.C., 2003.
28. Cate, M. A., Richards S. H., 2001. "An Evaluation of Large Truck Rollover Crashes on Tennessee Interstate Highways," Paper accepted for presentation at the TRB, 80th Annual Meeting, Washington D.C., 2001.
29. Jones, I.S., Whitfield, R.A., 1988. "Predicting Injury Risk with 'New Car Assessment Program' Crashworthiness Ratings." *Accident Analysis and Prevention*, Vol. 20 (6), pp. 411–419.
30. Shibata, A., Fukuda, K., 1994. "Risk Factors of Fatality in Motor Vehicle Traffic Accidents." *Accident Analysis and Prevention*, Vol. 26 (3), pp. 391–397.
31. Lui, K.J., McGee, D., Rhodes, P., Pollock, D., 1988. "An Application of a Conditional Logistic Regression to Study the Effects of Safety Belts, Principal Impact Points, and Car Weights on Drivers' Fatalities." *Journal of Safety Research*, Vol. 19, pp. 197–203.
32. O'Donnell C., Connor, D., 1996. "Predicting the Severity of Motor Vehicle Accident Injuries Using Models of Ordered Multiple Choice." *Accident Analysis and Prevention*, Vol. 28 (6), pp. 739-753.
33. Shankar, V.N., Mannering, F.L., 1996. "An Exploratory Multinomial Logit Analysis of Single-Vehicle Motorcycle Accident Severity." *Journal of Safety Research*, Vol. 27 (3), pp. 183–194.
34. Shankar, V.N., Mannering, F.L., Barfield, W., 1996. "Statistical Analysis of Accident Severity on Rural Freeways." *Accident Analysis and Prevention*, Vol. 28 (3), pp. 391–401.

35. Long, J. S., 1997. "*Regression Models for Categorical and Limited Dependent Variables*." Thousand Oaks, CA: Sage.
36. Ben-Akiva, M., Lerman, S. R., 1985. "Discrete Choice Analysis: Theory and Application to Travel Demand." The MIT Press.
37. Greene W., 1997. "*Econometric Analysis*," New York, NY: Macmillan Publishing Company, Third Edition.

LIST OF FIGURES AND TABLES

FIGURE 1 Post-crash fire and rollover crash.

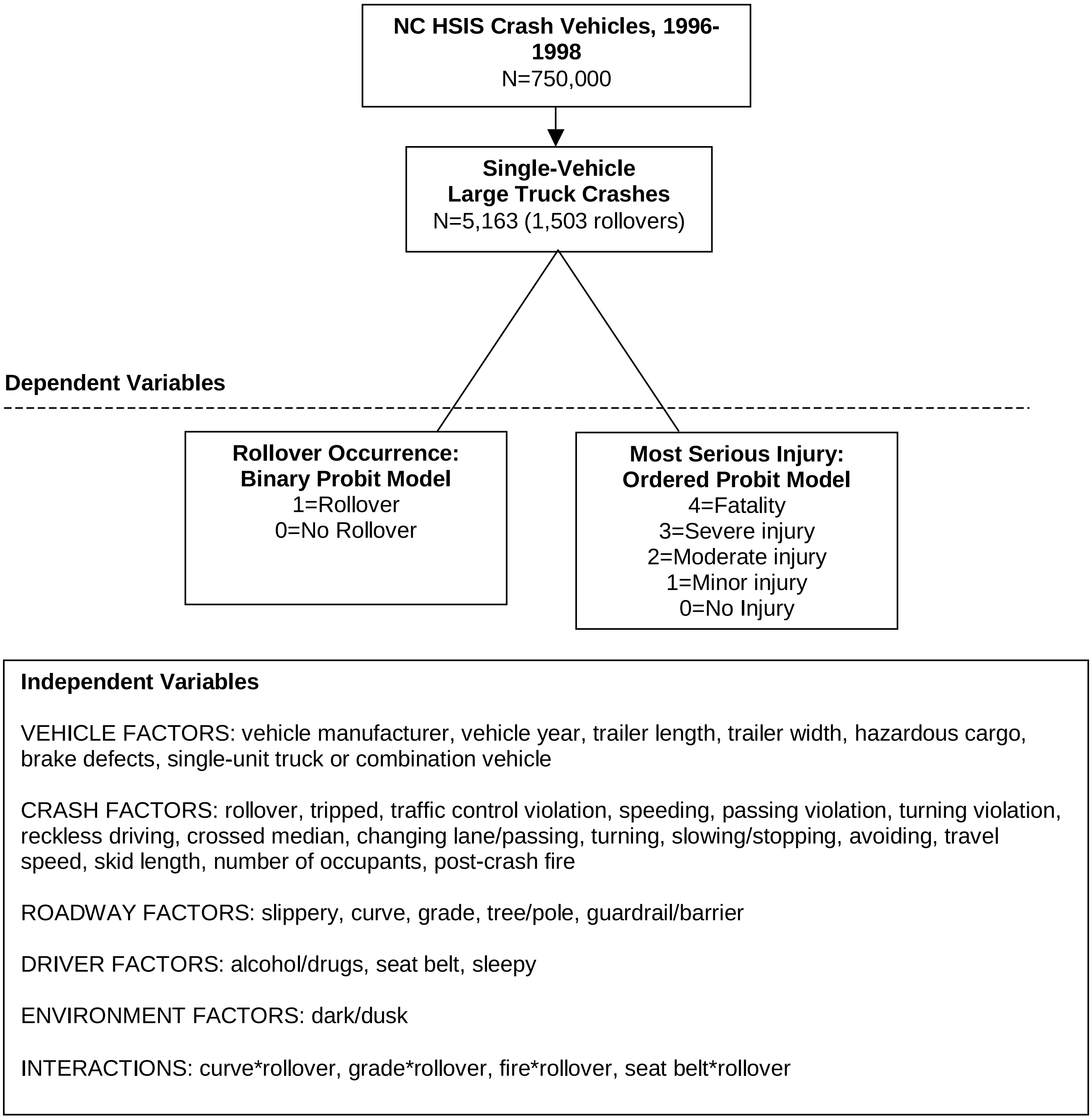
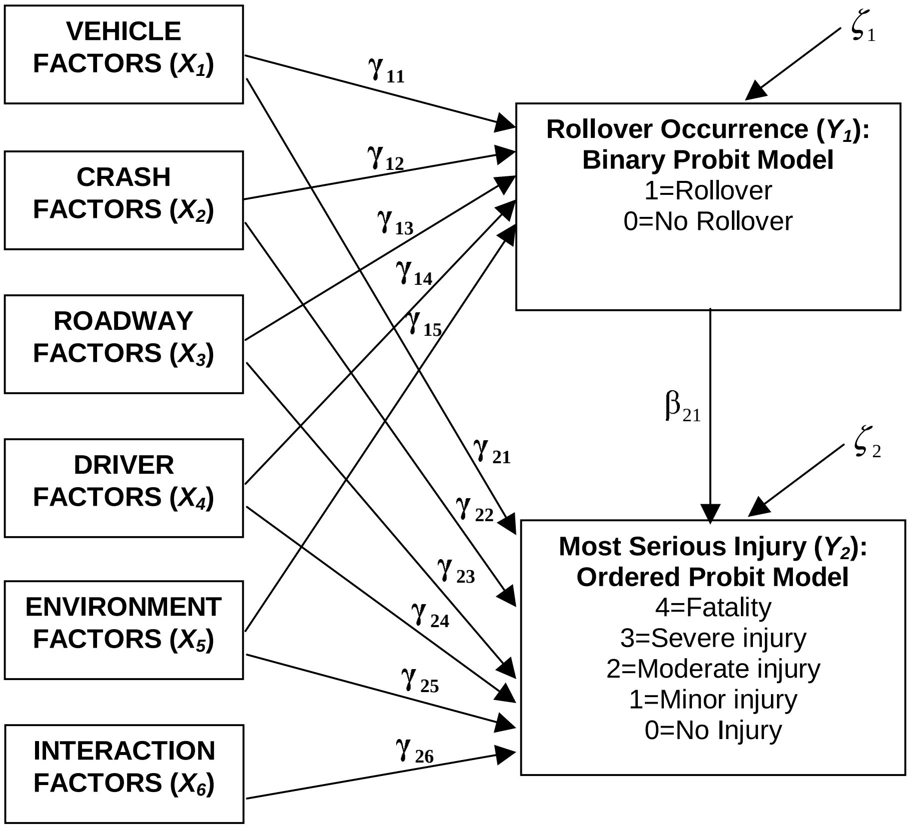


FIGURE 2 Data structure



$$Y_1 = \boldsymbol{\gamma}_{11}\mathbf{X}_1 + \boldsymbol{\gamma}_{12}\mathbf{X}_2 + \ldots\ldots + \boldsymbol{\gamma}_{15}\mathbf{X}_5 + \zeta_1$$
$$Y_2 = \boldsymbol{\gamma}_{21}\mathbf{X}_1 + \boldsymbol{\gamma}_{22}\mathbf{X}_2 + \ldots\ldots + \boldsymbol{\gamma}_{26}\mathbf{X}_6 + \beta_{21}Y_1 + \zeta_2$$

Where $\boldsymbol{\gamma}_{ij}$ are the estimated parameters for variables $\mathbf{X}_j$ that have a direct effect on Y_i, and $\mathbf{X}_j$.

FIGURE 3 Analysis structure

TABLE 1 Factors Associated with Large Truck Rollovers (Binary Probit Model)

Independent Variables	Rollover Model (N=5,098)		
	Coefficient (γ_{1j})	Mean	Marginals
Constant	-0.1518	1.000	-0.0474
VEHICLE FACTORS (X_1)			
Chevrolet	-0.0423	0.0853	-0.0132
Dodge	-0.6005*	0.0108	-0.1874
Ford	-0.0766	0.1738	-0.0239
Freightliner	0.0331	0.1436	0.0103
GMC	0.0054	0.0557	0.0017
International	0.0107	0.1758	0.0033
Isuzu	-0.0128	0.0143	-0.0040
Kenworth	0.0286	0.0614	0.0089
Mack	0.1721	0.0565	0.0537
Nissan	-0.2088	0.0071	-0.0652
Peterbilt	0.2235*	0.0551	0.0698
Toyota	-0.4525*	0.0088	-0.1412
Volvo	-0.0129	0.0269	-0.0040
Whit	-0.0562	0.0386	-0.0175
Pre-1992 Model Year	-0.1391**	0.5190	-0.0434
Trailer length over 45’	0.1319**	0.2224	0.0412
Trailer width over 100”	0.1175*	0.3539	0.0367
Defective brakes	-0.0097	0.0316	-0.0030
Single-unit truck	0.2172	0.4706	0.0678
CRASH FACTORS (X_2)			
Traffic control violation	-0.0878	0.0161	-0.0274
Speeding	0.5365**	0.3025	0.1675
Passing	0.6778*	0.0027	0.2116
Turning violation	-0.3093	0.0198	-0.0966
Reckless driving	0.6372**	0.0194	0.1989
Crossed median	0.3588**	0.0180	0.1120
Changing lanes/passing	0.1917	0.0155	0.0598
Turning	0.5063**	0.1022	0.1580
Slowing/stopping	-0.2250	0.0249	-0.0702
Avoiding object in road	-0.4897	0.0051	-0.1529
Travel speed	-0.0044**	43.8868	-0.0014
Skid length over 100’	-0.3384**	0.1858	-0.1056
Number of occupants	0.0450	1.1746	0.0140
ROADWAY FACTORS (X_3)			
Slippery surface	-0.2454**	0.3076	-0.0766
Curve	0.2948**	0.2279	0.0920
Grade	0.0250	0.2373	0.0078
Struck tree/pole	-0.7584**	0.1624	-0.2367
Struck guardrail/barrier	-0.2297**	0.1149	-0.0717
DRIVER FACTORS (X_4)			
Alcohol/drug presence	0.3425**	0.0228	0.1069
Sleepy	-0.0595	0.0247	-0.0186
ENVIRONMENTAL FACTORS (X_5)			
Darkness/Dusk/Dawn	-0.0738	0.2332	-0.0230
SUMMARY STATISTICS			
Log likelihood		-2,400	
Restricted log likelihood		-3,090	
Chi-squared		1,370	
Significance level (alpha)		0.000	

TABLE 2 Factors Associated with Large Truck Crash Injury Severity (Ordered Probit Model)

Independent Variables	Injury Severity Model (N=5,031) Coefficient (γ_{2j})	Mean
Constant	-1.0563**	
Endogenous variable (β_{21})		
Rollover	0.7295**	0.2956
VEHICLE FACTORS (X_1)		
Chevrolet	-0.0462	0.0821
Dodge	-0.1699	0.0105
Ford	-0.1052	0.1739
Freightliner	-0.1375	0.1453
GMC	-0.0617	0.0555
International	-0.0140	0.1771
Isuzu	-0.0404	0.0145
Kenworth	-0.1426	0.0618
Mack	0.0466	0.0570
Nissan	0.4375*	0.0072
Peterbilt	-0.1547	0.0557
Toyota	-0.0939	0.0089
Volvo	0.0097	0.0272
Whit	-0.0791	0.0390
Pre-1992 Model Year	0.0035	0.5232
Trailer length over 45’	-0.0609	0.2250
Trailer width over 100”	0.0004	0.3548
Hazardous material	0.4377**	0.0312
Defective brakes	0.2001*	0.0306
Single-unit truck	-0.1940	0.4675
CRASH FACTORS (X_2)		
Untripped rollover	0.0288	0.3691
Traffic control violation	0.3351**	0.0159
Speeding	0.1246**	0.3035
Passing	-0.5467	0.0028
Turning violation	-1.4012**	0.0189
Reckless driving	0.2058	0.0195
Crossed median	0.2330*	0.0181
Changing lanes/passing	0.0619	0.0157
Turning	-0.1223	0.1016
Slowing/stopping	-0.2303**	0.0252
Avoiding object in road	0.0706	0.0052
Travel speed	0.0071**	44.1115
Skid length over 100’	-0.2663**	0.1853
Number of occupants	0.1657**	1.1870
Post-crash fire	0.5684**	0.0244
ROADWAY FACTORS (X_3)		
Slippery surface	-0.0206	0.3091
Curve	0.1105*	0.2278
Grade	-0.0468	0.2361
Struck tree/pole	0.3560**	0.1600
Struck guardrail/barrier	0.2317**	0.1159
DRIVER FACTORS (X_4)		
Alcohol/drug presence	0.5647**	0.0231
Sleepy	0.1153	0.0250
No seat belt	0.4839**	0.0962
ENVIRONMENTAL FACTORS (X_5)		
Darkness/dusk/dawn	-0.0333	0.2304

ITERATIONS FACTORS (X_6)		
Curve and rollover	0.0083	0.0988
Grade and rollover	-0.0220	0.0795
Fire and rollover	0.5148*	0.0038
No seat belt and rollover	-0.0519	0.0467
THRESHOLDS		
μ_1	0.6666	0.0000
μ_2	1.5849	0.0000
μ_3	2.4986	0.0000
SUMMARY STATISTICS		
Log likelihood	-4,420	
Restricted log likelihood	-5,110	
Chi-squared	1,390	
Significance level (alpha)	0.000	

**=Significant association with injury severity (95% confidence level)
*=Significant association with injury severity (90% confidence level)

TABLE 3 Marginal Effects for Large Truck Crash Injury Severity Model

	Injury Severity Model (N=5,031)				
Independent Variable	**No injury**	**Minor**	**Moderate**	**Severe**	**Fatality**
Constant	0.3775	-0.1564	-0.17	-.0460	-0.0051
Endogenous variable					
Rollover	-0.2608	0.108	0.1175	.0318	0.0035
VEHICLE FACTORS (X_1)					
Chevrolet	0.0165	-0.0068	-0.0074	-.0020	-0.0003
Dodge	0.0607	-0.0251	-0.0273	-.0074	-0.0009
Ford	0.0376	-0.0156	-0.0169	-.0046	-0.0005
Freightliner	0.0491	-0.0204	-0.0221	-.0060	-0.0006
GMC	0.022	-0.0091	-0.0099	-.0027	-0.0003
International	0.005	-0.0021	-0.0023	-.0006	0.0000
Isuzu	0.0145	-0.006	-0.0065	-.0018	-0.0002
Kenworth	0.0509	-0.0211	-0.0229	-.0062	-0.0007
Mack	-0.0167	0.0069	0.0075	.0020	0.0003
Nissan	-0.1563	0.0648	0.0704	.0190	0.0021
Peterbilt	0.0553	-0.0229	-0.0249	-.0067	-0.0008
Toyota	0.0336	-0.0139	-0.0151	-.0041	-0.0005
Volvo	-0.0035	0.0014	0.0016	.0004	0.0001
Whit	0.0283	-0.0117	-0.0127	-.0034	-0.0005
Pre-1992 Model Year	-0.0013	0.0005	0.0006	.0002	0.0000
Trailer length over 45’	0.0218	-0.009	-0.0098	-.0027	-0.0003
Trailer width over 100”	-0.0001	0.0001	0.0001	.0000	-0.0001
Hazardous material	-0.1564	0.0648	0.0704	.0190	0.0022
Defective brakes	-0.0715	0.0296	0.0322	.0087	0.001
Single-unit truck	0.0693	-0.0287	-0.0312	-.0084	-0.001
CRASH FACTORS (X_2)					
Untripped rollover	-0.0103	0.0043	0.0046	.0013	0.0001
Traffic control violation	-0.1198	0.0496	0.0539	.0146	0.0017
Speeding	-0.0445	0.0184	0.02	.0054	0.0007
Passing	0.1954	-0.0809	-0.088	-.0238	-0.0027
Turning violation	0.5008	-0.2074	-0.2255	-.0610	-0.0069
Reckless driving	-0.0735	0.0305	0.0331	.0090	0.0009
Crossed median	-0.0833	0.0345	0.0375	.0101	0.0012
Changing lanes/passing	-0.0221	0.0092	0.01	.0027	0.0002
Turning	0.0437	-0.0181	-0.0197	-.0053	-0.0006
Slowing/stopping	0.0823	-0.0341	-0.0371	-.0100	-0.0011
Avoiding object in road	-0.0252	0.0104	0.0114	.0031	0.0003
Travel speed	-0.0025	0.0011	0.0011	.0003	0.0000
Skid length over 100’	0.0952	-0.0394	-0.0429	-.0116	-0.0013
Number of occupants	-0.0592	0.0245	0.0267	.0072	0.0008
Post-crash fire	-0.2031	0.0841	0.0915	.0247	0.0028
ROADWAY FACTORS (X_3)					
Slippery surface	0.0074	-0.0031	-0.0033	-.0009	-0.0001
Curve	-0.0395	0.0164	0.0178	.0048	0.0005
Grade	0.0167	-0.0069	-0.0075	-.0020	-0.0003
Struck tree/pole	-0.1272	0.0527	0.0573	.0155	0.0017
Struck guardrail/barrier	-0.0828	0.0343	0.0373	.0101	0.0011
DRIVER FACTORS (X_4)					
Alcohol/drug presence	-0.2018	0.0836	0.0909	.0246	0.0027
Sleepy	-0.0412	0.0171	0.0186	.0050	0.0005
No seat belt	-0.1729	0.0716	0.0779	.0211	0.0023
ENVIRONMENTAL FACTORS (X_5)					
Darkness/dusk/dawn	0.0119	-0.0049	-0.0054	-.0014	-0.0002

ITERATIONS FACTORS (X_6)					
Curve and rollover	-0.003	0.0012	0.0013	.0004	0.0001
Grade and rollover	0.0079	-0.0033	-0.0035	-.0010	-0.0001
Fire and rollover	-0.184	0.0762	0.0829	.0224	0.0025
No seat belt and rollover	0.0185	-0.0077	-0.0083	-.0023	-0.0002