THE EFFECT OF OCCUPANCY ON THE ROLLOVER PROPENSITY OF PASSENGER VEHICLES

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ABSTRACT

This paper provides a statistical assessment of the effect of occupancy on the rollover propensity of passenger vehicles such as cars, SUVs, minivans, pickup trucks and 15-passenger vans. A logistic regression model has been built to predict the probability of rollover as an outcome of a single vehicle crash, based on occupancy as well as various other vehicle, crash and driver-related factors. The model uses all police-reported crash data from selected states over the period from 1994 to 2001 from NHTSA's State Data System (SDS). The metric used to compare the relative risk of rollover among the vehicles is the probability of rollover conditional on a single vehicle crash having occurred. A binary logit model is estimated using the Maximum Likelihood (ML) approach. The resulting parameter estimates and test-statistics are used to assess significance of the explanatory variables and to estimate the probability of rollover for plausible scenarios. The analysis has shown that occupancy, along with speed and road geometry, has significant effect on rollover propensity. While the overall pattern points to an increasing risk of rollover with increasing occupancy in all passenger vehicle categories, the magnitude of increase varies significantly among the vehicle classes. In fact, the increase in the modeled risk of rollover from nominal (driver only) occupancy to full occupancy is most pronounced for 15-passenger vans followed by Minivans, SUVs, Pickup Trucks and Cars. Apart from the relative risks at nominal and full payloads, there is also a wide disparity in the predicted probabilities of rollover at various occupancies between the vehicles. In fact, on high-speed roads at full occupancy, 15-passenger vans depict the highest risk of rollover, followed by SUVs, Pickup Trucks, Minivans and Passenger Cars, in that order. Charts depicting predicted probabilities by occupancy for various hypothetical scenarios of crash factors are presented for each vehicle class.

INTRODUCTION

Prior research has shown that heavily loaded passenger vans are observed to have a higher rate of rollover as compared to lightly loaded vans [1]. NHTSA's consumer advisory of April 2001 on the rollover propensity of 15-passenger vans[1] was based on this research. This paper presents data analysis that seeks to extend the prior research on this topic by assessing the change in the risk of rollover with increasing occupancy for all passenger vehicles such as passenger cars, SUVs, pickup trucks, minivans and fifteen-passenger vans.

Fifteen-passenger vans differ from most light-trucks in that they have a larger payload capacity and the occupants sit fairly high up in the vehicle. Loading these vans to their Gross Vehicle Weight Rating (GVWR) has an adverse effect on the rollover propensity due to the increase in center-of-gravity height. Loading the vans with passengers and cargo also moves the center of gravity rearward, increasing the vertical load on the rear tires.

This paper provides a statistical assessment of the change in the risks of rollover, conditional on other factors remaining the same, when the passenger vehicles are loaded up to their designed seating capacity and are involved in a crash. Of specific interest is to determine the disparity in the risks of rollover at nominal occupancies and full occupancies for each class of passenger vehicle.

OBJECTIVE AND METHODOLOGY

The objective is to statistically model the risk of rollover with increasing occupancy levels using crash data that is representative of crashes of all severity. The desired metric is the probability of rollover, conditional on a single-vehicle crash having occurred. This conditional probability of rollover is chosen, as every single-vehicle crash is an opportunity for a rollover to occur and the vehicle characteristics that contribute to rollover are not obscured by the effect of the forces of collision. The binary response model for rollovers states that the probability of rollover, conditional on a single-vehicle crash having occurred, is a function of selected explanatory variables. The logit model, a widely used binary-response model, for rollover is

[1] While these vehicles actually have seating positions for a driver plus fourteen passengers, they are typically called 15-passenger vans. Also, these vehicles are actually classified as buses under 49 CFR 571.3.

the analytical technique used in this analysis. This paper introduces descriptive statistics on the rates of rollover for the various vehicle categories before presenting the results of the logit model.

DATA

Crash data from five states that are part of NHTSA's State Data System (SDS) were used in this study [Table 1].

Table 1. States and Years of Crash Data chosen for Study

States	Years
Florida	1994 to 2001
Maryland	1994 to 2001
North Carolina	1994 to 1999
Pennsylvania	1994 to 2000
Utah	1994 to 2001

The data are a census of all police-reported crashes in that State comprising of serious crashes (those resulting in a fatality or injury) as well as those that only resulted in damage to property. Consequently, the data are representative of the population of police-reported crashes in these States for those years.

The risk of rollover, measured in terms of modeled probability of rollover for 15-passenger vans will be compared with other types of passenger vehicles at various occupancy levels [Table 2]. Fully loaded conditions for the various vehicles are shown in Table 2.

Table 2. Occupancies assumed as fully loaded conditions by type of vehicle

Vehicle Type	Number of Occupants
15-Passenger Van	15+
Passenger Cars	4+
SUVs	4+
Pickup Trucks	4+
Minivans	7+

Some of the vehicles may have a designed seating capacity that exceeds those shown in Table 2. It is not possible to identify the seating configuration of passenger vehicles from NHTSA's databases or VINs. Also vehicles with much larger seating capacities than those mentioned in Table 2, especially SUVs, have been late entrants to the fleet. The latest data year in this analysis was 2001 and it is reasonable to assume that the fleet was heavily weighted towards the seating capacities mentioned in Table 2.

RESULTS

Table 3 provides a description of the population of single-vehicle crashes and rollovers being studied for each vehicle category.

Table 3. Single Vehicle Crashes and Rollovers by Vehicle Type

Vehicle Type	Crashes	Rollovers	%
15-P Vans	1,441	315	22%
Passenger Cars	423,760	66,318	16%
SUVs	61,968	23,927	39%
Pickup Trucks	98,282	26,187	27%
Minivans	16,205	2,746	17%

Overall, the incidence of rollover in single vehicle crashes for 15-passenger vans, expressed as a percentage of vehicles involved in such crashes, is comparable with those for other types of vehicles. SUVs had the highest incidence (39 percent) among all the vehicle categories while passenger cars had the lowest incidence rates (16 percent). However, the issue at hand is to analyze the rate of rollover at various occupancies for the different vehicle types.

Figure 1 compares the rates of rollover for various vehicle types by when they are loaded to or under half their seating capacity versus loaded to over half their seating capacity. For the sake of this analysis, passenger cars, SUVs and pickup trucks with two occupants or less, minivans with three occupants or less and 15-passenger vans with seven occupants or less are defined as vehicles loaded to or under half their capacity.

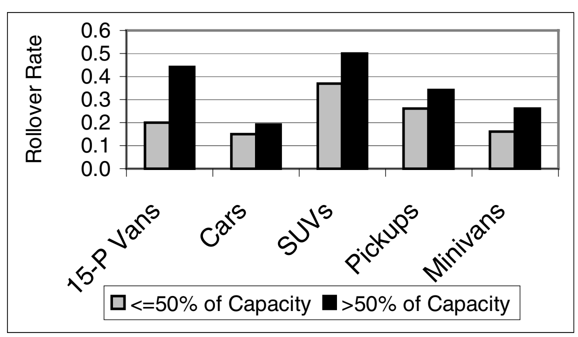

Figure 1. Rollover Rates in Single Vehicle Crashes by Vehicle Type and Occupancy.

As seen in Figure 1, when the vehicles are loaded to more than half of their seating capacity, the rates of rollover are higher as compared to when they are loaded to or under half their seating capacity.

However, the relative difference in the rates of rollover under the two different loading scenarios is most pronounced for 15-passenger vans. This relative difference is shown in Table 4 for other vehicle categories. It is noted that a 15-passenger van that is loaded to half its designed seating capacity has as many occupants as any other type of passenger vehicle that is fully loaded. The differences for all vehicle categories are statistically significant, as indicated by the p-values in Table 4.

Table 4. Rollover Rates in Single Vehicle Crashes by Vehicle Type and Occupancy

Vehicle Type	½ Seating Capacity or Under (a)	Over ½ Seating Capacity (b)	(b)/(a)
15-P Vans	0.20	0.44	2.2
Passenger Cars	0.15	0.19	1.3
SUVs	0.37	0.50	1.4
Pickup Trucks	0.26	0.34	1.3
Minivans	0.16	0.26	1.7
All Differences are Statistically Significant with p<0.001			

As shown in Table 4, occupancy seems to have a pronounced effect on the rates of rollover observed in single vehicle crashes. However, there are factors other than occupancy that can have an adverse effect on a vehicle's propensity to roll over. These may include the speed of travel, surface and weather conditions, experience/training of the driver and impaired driving. The speed of travel can be a significant factor in affecting rollover outcome because greater travel speed of the vehicle provides more energy to initiate rollover. Figure 2 un-confounds the effect of speed on the proportions shown in Table 4. In the absence of reliable measures of travel speed, the posted speed limit at the scene of the crash is used as a proxy for the speed of travel. Figure 2 shows, by vehicle type, the composition of the rollovers by occupancy and the speed limit of the road they were traveling at the time of the crash. The numbers in each of the bars in Figure 2 indicate the proportion of the rollovers in that category that occurred on high-speed roads (50+ mph). So, 62 percent of rollovers of 15-passenger vans that loaded to half or under half of their designed capacity were in high-speed roads. In comparison, 91 percent of rollovers involving 15-passenger vans that were loaded at or above half their designed seating capacity occurred on high-speed roads. Figure 2 shows that heavily loaded 15-passenger vans have a higher proportion of their rollovers on high-speed roads than do other light vehicles. Under similar circumstances, SUVs have comparable risks of rollover too.

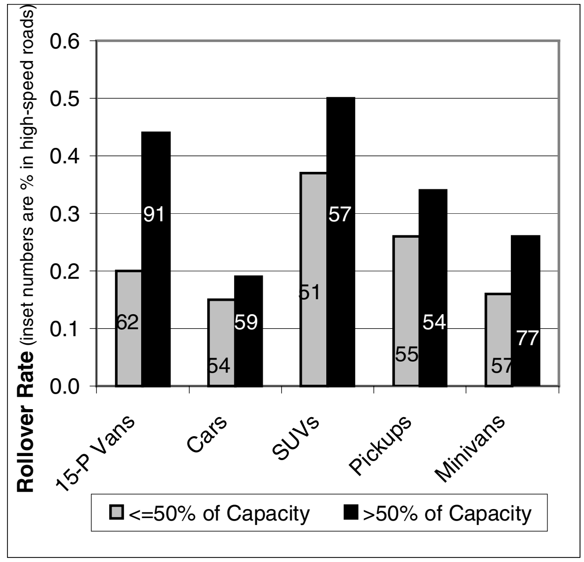

Figure 2. Rollover Rates in Single Vehicle Crashes by Vehicle Type, Occupancy and proportion in High Speed Roads.

Even though the rate of rollover under heavily loaded scenarios for 15-passenger vans is comparable with SUVs, it is much higher than the rate for other types of vehicles. It will be noteworthy to examine the relative disparity in the rates of rollover between heavily loaded (½ seating capacity or over) and lightly loaded (under ½ seating capacity) scenarios on high-speed roads. Table 5 depicts this relative risk ratio.

Table 5. Rollover Rates by Occupancy and Vehicle Type in Single Vehicle Crashes in High-Speed Roads (50+ mph)

Vehicle Type	½ Seating Capacity or Under (a)	Over ½ Seating Capacity (b)	Rel. Diff. (Ratio)
15-P Vans	0.30%	0.62%	2.1
Passenger Cars	0.22%	0.26%	1.2
SUVs	0.49%	0.61%	1.2
Pickup Trucks	0.36%	0.43%	1.2
Minivans	0.26%	0.34%	1.3
All Differences are Statistically Significant with p<0.001			

The disparity in the rates of rollover between light and heavy loading conditions on high-speed roads is the largest for 15-passenger vans. However, one can assess the true effect of occupancy on rollover propensity by taking into account the effect of various other factors that can affect rollover outcome.

Logistic Regression Modeling

Statistically, a logistic regression model is very suitable to predict rollover as a dichotomous outcome (yes or no), based on explanatory variables [2]. Logistic regression permits the joint estimation of the effect or significance of a variable in affecting rollover. If **Y** denotes the dependent variable in a binary-response model for rollovers, **Y** is equal to 1 if there is a rollover and 0 otherwise. The goal is to statistically estimate the probability that **Y=1**, considered as a function of explanatory variables. The logit model, a widely used binary-response model, for rollover is:

$$P(Y = 1 \mid \mathbf{X} = x) = \frac{1}{[1 + e^{(\alpha + \beta x)}]} \quad (1).$$

This model can be rewritten, after taking the natural logarithm of both sides as:

$$Ln\left(\frac{P}{(1-P)}\right) = \alpha + \beta x \quad (2).$$

where α is the intercept, β is the vector of coefficients and x is a vector of explanatory variables.

The explanatory variables used to model rollover as an outcome are shown in Table 6. The model uses metrics to represent various crash and driver-related characteristics and more importantly, the number of occupants in the vehicle. That is, for each vehicle type

Logit (Pr(Rollover)) = OCCUPANCY DARK STORM FAST HILL CURVE BADSURF MALE YOUNG OLD DRINK DUMMYMD DUMMYNC DUMMYPA DUMMYUT.

The factors used in the model mirror those used in NHTSA's New Car Assessment Program (NCAP) studies [3] with the exception of the Static Stability Factors and dynamic test results. This study is intended to provide insight into rollover propensity for broad vehicle categories and not specific models, which would have required the inclusion of such metrics.

Also included in the regression model were four variables DummyMD, DummyNC, DummyPA and DummyUT. The variables DUMMY<State> represent the change in Logit(Pr(Rollover)) due to the crash's taking place in that State as compared to an otherwise similar crash in Florida. They are included to control for differences in traffic patterns and reporting practices that effect rollover rates between the States.

Table 6. Rollover Rates by Occupancy and Vehicle Type in Single Vehicle Crashes in High-Speed Roads (50+ mph)

Variable	Description	Levels
Occ	Number of Occupants	**1 to 15+**
Dark	Light Condition	**1** if dark; **0** if not dark
Storm	Stormy Weather	**1** if stormy; **0** if not
Fast	Speed (Speed Limit as Proxy)	**1** if 50+ mph else **0**
Hill	Hilly Gradient	**1** if yes else **0**
Curve	Road Curves	**1** if yes else **0**
Badsurf	Adverse Roadway Surface Conditions	**1** if yes else **0**
Male	Male Driver	**1** if yes else **0**
Young	Young Driver (Under 25)	**1** if yes else **0**
Drink	Driver Impairment	**1** if yes else **0**

The roadway function class, i.e., if the site of the crash was a rural or urban area, was not used in the regression due to the unavailability of data. However, it may be assumed that speed limit, curve and roadway surface conditions may account for many of the differences reflected in the rural/urban dichotomy. The regression was done within each vehicle type in order to assess the effect of the various covariates on rollover outcome. The results of logistic regression model are presented in Table 7. The test statistics indicate the goodness of fit of model for each vehicle category.

Table 7. Results of Logistic Regression Model by Vehicle Category

Vehicle	Degrees of Freedom (DF)	$p > \chi^2$
15-P Vans	15	**< 0.0001**
Passenger Cars	15	**< 0.0001**
SUVs	15	**< 0.0001**
Pickup Trucks	15	**< 0.0001**
Minivans	15	**< 0.0001**

The joint estimation using the logistic regression model reveals that the variables with the most significant impact on rollover outcome among all vehicle categories are:

- **Fast** (high-speed road, 50+ mph)
- **Occupancy** (Number of vehicle occupants)
- **Curve** (curved geometry at site)

Table 8 depicts the estimates of coefficients for the significant variables by vehicle category. As seen in Table 8, occupancy, speed and curve are significant factors in predicting rollover outcome for all vehicle categories as indicated by their low p-values.

Table 8. Parameter estimates for Occupancy, Speed and Road Curvature by Vehicle Type

Vehicle	Estimate (Standard Error)	$p > \chi^2$
Occupancy		
15-P Vans	0.1135 (0.0229)	**< 0.0001**
Passenger Cars	0.0593 (0.0059)	**< 0.0001**
SUVs	0.1911 (0.0120)	**< 0.0001**
Pickup Trucks	0.1257 (0.0126)	**< 0.0001**
Minivans	0.1163 (0.0176)	**< 0.0001**
Speed		
15-P Vans	1.6138 (0.1756)	**< 0.0001**
Passenger Cars	0.8977 (0.0106)	**< 0.0001**
SUVs	0.9654 (0.0258)	**< 0.0001**
Pickup Trucks	0.9816 (0.0184)	**< 0.0001**
Minivans	1.1672 (0.0553)	**< 0.0001**
Curved Geometry		
15-P Vans	0.6874 (0.1802)	**< 0.0001**
Passenger Cars	0.6362 (0.0105)	**< 0.0001**
SUVs	0.4732 (0.0230)	**< 0.0001**
Pickup Trucks	0.6027 (0.0183)	**< 0.0001**
Minivans	0.5089 (0.0573)	**< 0.0001**

The coefficient vector β from the logistic regression model yields predicted probability of rollover as shown in Figure 3. Figure 3 represents the probabilities of rollover, conditional on a single vehicle crash, for a "favorable" scenario in terms of factors that affect rollover as an outcome. The "favorable" scenario is a combination of favorable driving conditions and factors for the terms included in the logistic regression model. This includes good light and weather conditions, low-speed road (under 50 mph), flat terrain, straight and good road conditions and no driver impairment.

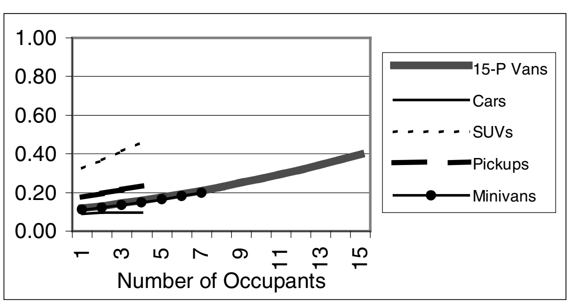

Figure 3. Conditional (single vehicle crash) probability of Rollover with Occupancy under normal scenarios.

As seen in Figure 3, the probability of rollover at nominal loads (driver only) shows a wide disparity among the vehicle types. SUVs have the highest probability of rollover under these circumstances followed by pickup trucks, 15-passenger vans, minivans and passenger cars. Under fully loaded conditions, SUVs and pickup trucks have comparable probabilities of rollover and were the highest among all vehicle categories. Pickup trucks, minivans and passenger cars exhibit probabilities that are lower than that of SUVs and 15-passenger vans under the same circumstances.

Figure 4 depicts the distribution of the probability of rollover for what can be considered as an "adverse" scenario to affect rollover. The adverse scenario includes statistically significant variables, **fast** and **curve**. The probabilities depicted in Figure 4 are for crashes occurring on curved areas on high-speed roads and other factors remaining normal.

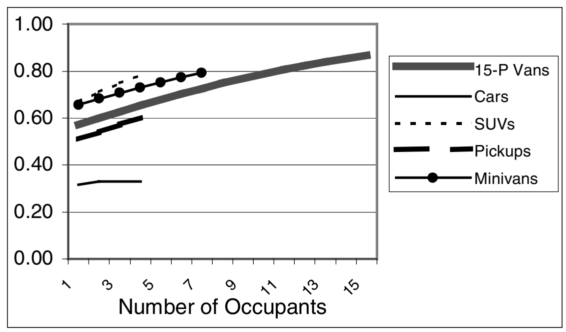

Figure 4. Conditional (single vehicle crash)_probability of Rollover with Occupancy under adverse scenarios.

Fifteen-passenger vans exhibit the highest probability of rollover under adverse scenarios at fully loaded conditions. Minivans, SUVs, pickup trucks and passenger cars have a lower probability of rollover under fully loaded scenarios under adverse driving scenarios.

As seen in Figures 3 and 4, the probability of rollover as indicated by the logistic regression model indicates a progressively worsening risk of rollover with increasing occupancy for all vehicle types including 15-passenger vans. The probability of rollover with just the driver in the vehicle ranges from 0.12 in favorable conditions to above 0.57 in adverse conditions. However, when the van is loaded to or above its designed seating capacity, the corresponding probabilities increase to an estimated 0.39 and 0.87, respectively. This trend, while observed for all types of vehicles, is most pronounced for 15-passenger vans because of the sheer multiplicative effect of the larger seating capacity for 15-passenger vans. In order to put the conditional probabilities into perspective, Tables 7 and 8 present the disparity in the risks of rollover between nominal and fully loaded scenarios under normal and adverse driving conditions, respectively.

Table 9. Probability of Rollover under Nominal and Fully Loaded Conditions in Single Vehicle Crashes under *Normal* Scenarios

Vehicle Type	Driver Only (Nominal)	Fully Loaded	Rel. Diff. (Ratio)
15-P Vans	0.119	0.398	3.34
Passenger Cars	0.091	0.096	1.05
SUVs	0.326	0.462	1.42
Pickup Trucks	0.176	0.237	1.35
Minivans	0.110	0.149	1.35

Table 10. Probability of Rollover under Nominal and Fully Loaded Conditions in Single Vehicle Crashes under *Adverse* Scenarios

Vehicle Type	Driver Only (Nominal)	Fully Loaded	Rel. Diff. (Ratio)
15-P Vans	0.574	0.868	1.50
Passenger Cars	0.317	0.329	1.03
SUVs	0.671	0.783	1.17
Pickup Trucks	0.510	0.602	1.18
Minivans	0.656	0.793	1.21

As seen in Tables 9 and 10, among passenger vehicles, 15-passenger vans seem to exhibit the greatest disparity in the risks of rollover between nominal and fully loaded conditions for both normal and adverse driving scenarios. While SUVs show comparable probabilities of rollover under both scenarios, the disparity between the risks is less than that for 15-passenger vans.

In a comparison of extremes, there is a seven-fold increase in the risk of rollover between lightly loaded 15-passenger vans under normal scenarios as compared to fully loaded ones under adverse scenarios [0.119 versus 0.868].

CONCLUSIONS

While the increment in the risk of rollover with every unit increase in occupancy for 15-passenger vans was comparable to other passenger vehicles, 15-passenger vans exhibited a much higher risk of rollover when they were loaded at or above their designed seating capacity under both normal and adverse scenarios. Speed and geometry of the road were other factors that significantly affect the risk of rollover for all types of passenger vehicles.

The disparity in the risk of rollover between nominal and fully loaded conditions is the greatest for 15-passenger vans. This is of significant interest for drivers of vanpools and other organizations that use these vehicles. Drivers of these vehicles should be educated to this disparity in the risk of rollover when they are driving by themselves as compared to when they are transporting a vanload of people.

REFERENCES

[1] Garrott, R.W., (2001) *The Rollover Propensity of Fifteen-Passenger Vans*, National Highway Traffic Safety Administration, Department of Transportation.

[2] Paul D.Allison, "*Logistic Regression using the SAS System*", Users Press, 2001.

[3] NHTSA, New Car Assessment Program; Rollover Resistance, 49 CFR Part 575, [Docket No. NHTSA-2001- 9663; Notice 3].