A CLASSIFICATION MODEL FOR PREDICTION OF ROLLOVER CRASH SEVERITY

Dinesh Sharma
National Highway Traffic Safety Administration
Washington, DC, U.S.A.

Santokh Singh
URC Enterprises, Inc.
Olney, MD, U.S.A.

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ABSTRACT

Crash severity can be defined as the potential of a crash to cause an injury or fatality. In the National Automotive Sampling System – Crashworthiness Data System (NASS-CDS), the crash severity of a rollover is assessed by estimating the magnitude of maximum intrusion and crush in the damaged vehicle. Several studies have shown that the number of quarter turns and roof intrusion are significant factors influencing the injury outcome. These studies mainly investigate the relationship between injury severity and vehicle-, crash-, or occupant-related variables. The purpose of this study is to develop a model that uses both vehicle- and crash-related parameters to estimate the rollover crash severity based on injury outcome.

In this study, the data mining technique called discriminant analysis is used to build a predictive model. Of the several rollover-related variables considered as candidate predictors, the maximum intrusion, number of quarter turns, and estimated distance from trip point to final rest position show significant correlations with the maximum abbreviated injury scale (MAIS) and hence are selected as predictors for the model.

Since one of the predictors, the estimated distance from trip point to final rest position, was introduced in the NASS-CDS data in 2006, this study is based upon two years (2006 and 2007) of data. To eliminate the confounding effect of external sources of injury, only non-ejected occupants are considered. The data is also screened to include only the maximum intrusion in the vehicle and the occupant with maximum MAIS in the vehicle.

The discriminant function is used in building the model. Given the specific values of the predictors for a rollover case, the final model predicts the injury outcome in rollovers as minor, moderate, and severe with sufficient accuracy. The model can be used to extract comparable rollover cases to understand injury mechanisms that can be used to develop vehicle crashworthiness countermeasures.

INTRODUCTION

The rollover of a vehicle is a complex phenomenon involving several pre-rollover maneuvers at varying speeds, tripping force, road and off-road terrain, vehicle geometry, type of rollover, and direct impact with the ground or other object. Due to this complexity, the reconstruction of a rollover is extremely difficult as is the estimation of its severity. However, the rollover crash parameters can be used to assess the crash severity based on the injury outcome.

Several factors have been shown to play roles in injury outcome of a rollover crash. In earlier studies researchers have identified the number of quarter turns, number of times a roof hits the ground, and vertical roof intrusions as statistically significant factors that are associated with the injury risk in a single vehicle rollover [1, 2, 3, 4.] These post crash parameters are also directly related to the pre-crash velocity and crash energy and hence are considered as appropriate surrogates for a crash severity measure. However, each of these surrogates provides only a partial measure of crash severity. Nonetheless, the significance of the contribution of each of these surrogates to the crash severity can be exploited to predict the severity of a rollover crash in terms of injury risk.

This study develops a model that can predict the injury outcome in rollovers based on certain crash and vehicle parameters. The right choice of predictors which relate to injury outcome of a crash is crucial in the model building process.

Descriptive analysis is conducted on NASS-CDS rollover data to identify crash severity surrogates (rollover parameters) that show statistically significant relation with the injury observed in the rollover vehicle. These parameters together with the injury severity measure, MAIS are then used to develop a multidimensional classification model that predicts the crash severity in terms of injury outcome. The efficacy of the model is demonstrated through test cases not involved in building the model. Weighted data are used for both preliminary analysis and model development.

ANALYSIS DATA PREPARATION

The rollover data from NASS-CDS is used in this study. This crash database is a national representative sample of tow-away crashes that occur on US highways. Every year, detailed information on vehicle damage, injury, and injury mechanism is collected on about 4,500 of these light passenger motor vehicle crashes [5]. The data consists of over 600 variables that describe crash events, damage to vehicle, crash forces involved, injuries to the victim and injury causation mechanisms for frontal, side, rear, and rollovers crashes. In 2006, a number of additional rollover-related variables were introduced in the NASS-CDS to facilitate comprehensive analyses of rollover data. The new variables include:

- Estimated distance from the trip point to final rest position (to be referred to as "estimated distance"): The purpose of this variable is to determine the estimated distance from trip point to the final rest position of the rollover vehicle. The measurements (in meters) are obtained along the linear path.

- Maximum vertical and lateral crush: The crush is measured on the vehicle component in the greenhouse area of the vehicle. The maximum vertical and lateral crushes are measured on the exterior of the vehicle and could be at different locations. In this study, only maximum vertical crush is considered and is referred to as "maximum vertical crush."

- Interrupted roll: In NASS-CDS, a rollover event is categorized as interrupted if the vehicle's rollover sequence is acted upon by another vehicle or object between the trip point and final rest position. As an example, the vehicle strikes a tree with its top during the rollover sequence or contacts an object in the environment. This impact should have an effect on the distance the vehicle would move from the trip point to final rest position.

In order to make use of the information available on the above described variables, the data used in the analysis is limited to the period 2006 to 2007 that provided a sample of 1,582 rollover vehicles. This sample includes both belted and nonbelted occupants. To eliminate irrelevant sources of variation (from a statistical point of view,) the data is segmented by using the following criteria:

- Injury source: Internal to the vehicle

- Occupants: Non-ejected occupants 13 years and older. A partially ejected occupant is included in the data if the source of the occupant's MAIS is the vehicle's interior component.

- VMAIS: Maximum of the MAIS per vehicle. Injury risk is evaluated by MAIS for each occupant. The MAIS describes the highest abbreviated injury severity score (AIS), based on mortality risk sustained by an occupant. The scale ranges from minor (AIS 1) through maximum (AIS 6) injuries and unknown (AIS 7). Only the occupant with maximum MAIS in the vehicle is selected.

- INTRUSION: Maximum value of all intrusions is coded for a vehicle. Intrusion of the windshield, hood, outside surface, and exterior objects are excluded. The windshield may sag post-crash, for example, in hot weather, thereby providing unreliable measurements during vehicle inspection. In NASS-CDS the magnitude and location of intrusion is coded for each intruding component. Intrusion results whenever the internal boundary of the passenger compartment is moved inward due to direct or indirect damage resulting from the application of a crushing force to the exterior of a vehicle. The intrusion is coded in the dominant crush direction. For example, the roof side rail may have both lateral and vertical intrusions. Only the intrusion with the greater magnitude is coded along with the direction of the maximum intrusion.

The maximum MAIS observed in the vehicle is not linked to maximum intrusion at that seating position. In the subsequent discussion, a vehicle selected through the above criteria will be referred to as the case vehicle. Data cleaning and removal of unknowns from the 1,582 case vehicles reduced the sample size to 607 that yields weighted estimate of 21,841 case vehicles.

PRELIMINARY ANALYSIS

A preliminary analysis is conducted on the weighted data to gain insight into the rollover phenomenon. Several aspects of the rollovers are considered for this purpose. These include the number of quarter turns, maximum MAIS for the vehicle, maximum intrusion, maximum vertical crush, and whether or not rollover was interrupted.

Number of quarter turns in rollovers: In terms of quarter turns, 70 percent of rollovers resulted in either two (34%) or four (36%) quarter turns (Figure 1). Interestingly, a much higher percentage (85%) of vehicles had an even number of quarter turns as compared with 15 percent that had an odd number of quarter turns. It indicates that at the final rest, a rollover vehicle, in general, tends to end up either on its wheels or roof.

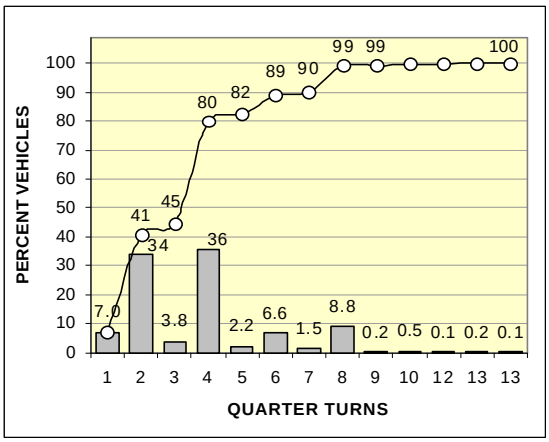

Figure 1. Frequency distribution of vehicles involved in rollovers over number of quarter turns (Data source: NASS-CDS 2006-2007).

Figure 1 also presents cumulative frequency distribution of quarter turns. The line graph in this figure shows that only 7 percent of case vehicles had one quarter turn. Almost 80 percent of the case vehicles had four or less number of quarter turns.

Vehicle maximum MAIS: Figure 2 shows the distribution of injury severity levels in case vehicles as measured by VMAIS. The data shows that most (91%) rollover crashes resulted in VMAIS 0-2 injuries. Only 9 percent of the vehicles had serious occupant injuries (VMAIS 3 or greater.) Seventy-nine percent of the occupants in the sample were belted. The belt use may have influenced the injury outcome. The high counts of minor and moderate injuries could be due to the high percentage of belt use. The frequency distributions of VMAIS for the sample and the overall rollover population were similar.

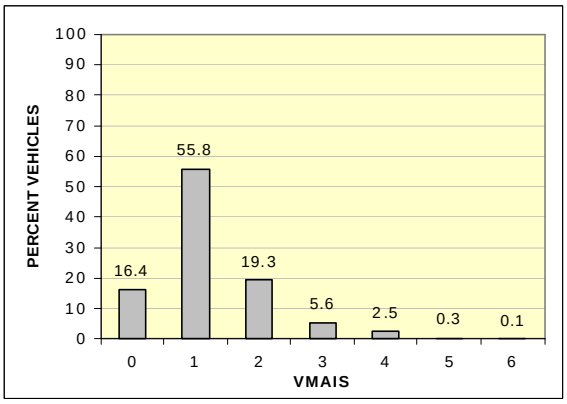

Figure 2. Frequency distribution of vehicles involved in rollovers over VMAIS levels (Data source: NASS-CDS 2006-2007).

Vehicle Maximum Intrusion: To study how the intrusion varies over VMAIS, averages of maximum intrusion are estimated for each of the VMAIS level. Intrusion is measured on the interior surface of the passenger compartment. The maximum value of all intrusions for the case vehicle is considered in this study. The results presented in Figure 3 show that average maximum intrusion increases with increasing injury level – the higher the injury, the higher is the average intrusion. However, based on the way the data was prepared for this study, higher intrusion at a specific occupant position does not necessarily mean that there is a higher chance of injury at that occupant position.

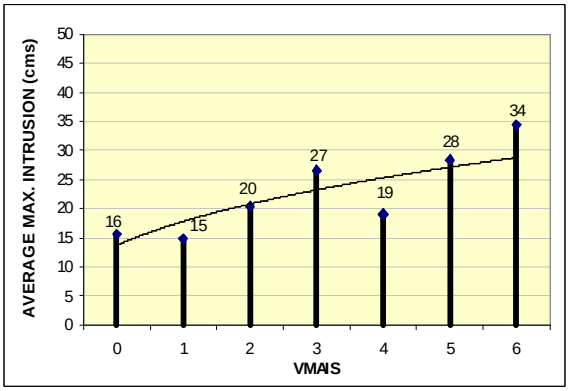

Figure 3. Average maximum intrusion over VMAIS (Data source: NASS-CDS 2006-2007).

The average maximum intrusion varies from 15 centimeters for VMAIS 1 to 34 centimeters for VMAIS 6. Thus, the data supports the assumption

that maximum intrusion is an appropriate surrogate for crash severity in terms of the injury outcome.

Maximum Vertical crush: The averages of maximum vertical crush over VMAIS are shown in Figure 4. The maximum vertical crush is measured on the exterior surface, typically roof or pillars of the vehicle. As in the case of intrusion, maximum vertical crush also shows a positive relationship with VMAIS, though not as strong as for the intrusion.

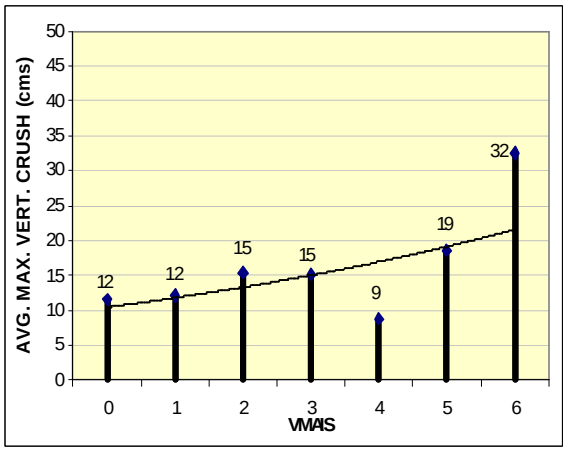

Figure 4. Average Maximum vertical crush over VMAIS (Data source: NASS-CDS 2006-2007).

In a rollover crash, interruption of a vehicle's rollover sequence plays a significant role in determining both vehicle intrusion and maximum vertical crush and consequently the injury risk. The interrupted rollovers result in higher intrusion and hence are more severe, in general [6].

A detailed analysis of the data with focus on interruption status of the case vehicle is conducted to study its relation with maximum intrusion. The results show that on the average, interrupted rollovers resulted in 29 centimeters of intrusion as compared with 21 centimeters for the rollovers that were not interrupted. The statistical test is performed on the difference between the two averages (Figure 5). This analysis shows that the average maximum intrusion for the Interrupted category is significantly (95% confidence level) higher than for the not-interrupted. The averages of the maximum intrusion for the interrupted and not-interrupted categories over VMAIS are shown in Figure 5. The increasing trend of average max intrusion over VMAIS in the sample containing both categories is also observed for each of the categories when considered separately.

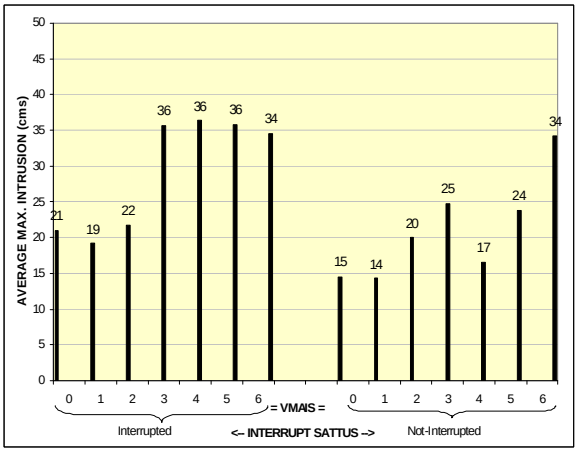

Figure 5. Comparison: average maximum intrusion of interrupted and not-interrupted rollovers over VMAIS (Data source: NASS-CDS 2006-2007).

It indicates that the likelihood of serious injury outcome is more in an interrupted rollover as compared with the one that is not interrupted.

The above analyses of the weighted data provide sufficient evidence to consider maximum intrusion, quarter turns, and maximum vertical crush as predictors in a model that could predict the injury outcome of a rollover crash. The model proposed in this study also considers the new variable, estimated distance as one of the predictors.

CLASSIFICATION MODEL FOR PREDICTING INJURY OUTCOME IN A ROLLOVER

One of the multivariate classification techniques, Discriminant analysis is used to build the predictive mode. This analysis provides a discriminant function that has the potential to classify new multivariate observation(s) into one of the predefined groups based on the knowledge of the multi-attributes. In the present context, the developed model (discriminant function) can predict injury outcome in rollover crashes based on maximum intrusion, estimated distance, quarter turns, and maximum vertical crush of a rollover vehicle. The modeling procedure consists of developing a discriminant score for each of the predefined groups, as well as computing the posterior probabilities of a case belonging to these groups. The decision about its most affine group is taken based on the highest probability. The following sections provide specific details of the modeling procedure.

Model Assumptions

The basic requirement of the modeling procedure (discriminant analysis) used in this study is the multivariate normality of the data with respect to predictor variables in each of the seven classifying groups defined by the response variable VMAIS (= 0, 1, 2, 3, 4, 5, 6.) To satisfy this assumption, logarithmic transformation is applied to the variables, maximum intrusion and estimated distance and square root transformation to the variables, quarter turns and maximum vertical crush.

Modeling Methodology

The classification criterion consists of estimates of the generalized squared distances that are based on the pooled covariance matrix. Specifically, quadratic form of the discriminant function is used. Each observation is classified into the group from which it has the smallest generalized distance. In general, the generalized squared distance of an observation $\underline{X}$ from group G_i is defined as

$$D_i^2(\underline{x}) = (\underline{x} - \underline{mean}_i)'(V_p)^{-1}(\underline{x} - \underline{mean}_i)\ , \qquad (1)$$

where $\underline{mean}_i$ denotes the vector of population means for the *i-th* group and V_p is the pooled covariance matrix. The discriminant scores are computed by the formula: $-0.5D_k^2(\underline{x})$. The classification is done based on both the discriminant score and the posterior probability $p(i/\underline{x})$ of $\underline{x}$ belonging to group, which is defined as

$$p(i/\underset{\sim}{x}) = \frac{exp(-0.5D_i^2)}{\sum_{k=1}^{K} exp(-0.5D_i^2)} \qquad (2)$$

Specifically, the ith case is classified into group k if the setting $i = k$ produces largest value of the posterior probability $p(i/\underline{x})$ of $\underline{x}$ belonging to group i or the smallest value of the discriminant score $D_i^2(\underline{x})$.

Development of the Classification Model

The modeling methodology was initiated by the stepwise discrimination. This statistical technique performs statistical tests to select (if a predictor variable has association with the grouping variable) or remove a variable (if the predictor variable is redundant.) None of the selected predictor variables was dropped as a result of this procedure.

Two sets of data were used; namely 'training data' and "test data." While training data were used to build the model, the test data were used to validate the model. A random sample of 50 cases was selected from the analysis data to be used as test cases. While developing the model, the dataset used as training data excluded only one test case at a time. Having built the model, a case reserved as the test case at this iteration was classified using the model. SAS 9.1 [7] was used to perform the discrimination procedure. Based on the 607 rollover case vehicles (21,841 weighted), the distance (1) was estimated using the sample generalized squared distance function:

$$\hat{D}_i^2(\underline{x}) = (\underline{x} - \underline{\bar{x}}_i)'(S_p)^{-1}(\underline{x} - \underline{\bar{x}}_i)\ , \qquad (3)$$

where sample estimates $\underline{\bar{x}}_i, i=0,1,2,3,4,5,6$ of the means for the VMAIS–based groups are

$$\underline{\bar{x}}_0 = (2.49853,\ 2.28694,\ 1.55858,\ 2.92274),$$
$$\underline{\bar{x}}_1 = (2.46709,\ 2.37454,\ 1.83361,\ 3.16926),$$
$$\underline{\bar{x}}_2 = (2.85176,\ 2.96116,\ 2.10097,\ 3.50653),$$
$$\underline{\bar{x}}_3 = (3.11915,\ 3.04347,\ 2.07973,\ 3.48200),$$
$$\underline{\bar{x}}_4 = (2.60471,\ 2.65131,\ 1.74369,\ 2.24281)$$
$$\underline{\bar{x}}_5 = (3.25489,\ 2.96713,\ 2.11604,\ 4.17312),$$
$$\underline{\bar{x}}_6 = (3.33704,\ 1.96309,\ 1.24798,\ 5.21871);$$

and the estimated pooled covariance matrix is given by

$$S_p = \begin{pmatrix} 153.785 & 22.024 & 2.387 & 211.462 \\ 22.024 & 197.468 & 89.787 & 144.703 \\ 2.386 & 89.786 & 84.584 & 80.119 \\ 211.461 & 144.703 & 80.119 & 919.446 \end{pmatrix}$$

Based on these estimates and values of the predictors for each case, i.e., $\underset{\sim}{x}$, scores $-0.5\hat{D}_k^2(\underline{x})$ (equation (3)) and posterior probabilities $p(i/\underline{x})$ in (2) were estimated to classify each of the test cases.

Implementation of the Model – Prediction and Validation

It is presumed that the severity of a crash can be assessed by its injury outcome. For prediction and validation purpose, the injury outcome in rollover is defined as

Minor, if VMAIS = 0, 1;
Moderate, if VMAIS = 2;
Severe, if VMAIS = 3, 4, 5, 6.

Implementation of the model was done through validation of 50 cases. The results are presented in Table 1. It should be noted that although this table presents the model-based classification for all 50 test cases, only one case was used as a test case at a time, while the rest are used in building the model. This table presents NASS Caseid and the predictor variables, intrusion, estimated distance, quarter turns, and maximum vertical crush for the test cases.

Table 1 also shows the observed and predicted injury outcome which, due to the probabilistic nature of the model, may not always agree, thus resulting into a match or mismatch. However, a mismatch may not necessarily mean an incorrect prediction. An injury outcome observed in a case vehicle might have been influenced by the occupant-related factors, such as seating position relative to the damage. The model predicts the injury outcome rather based on the vehicle and crash parameters. To bring about this point, a clinical analysis of some matched and mismatched test cases is presented in following sections.

The results show that for about 66 percent of the test cases, the predicted injury outcome matches the observed injury outcome. In addition, for 62 percent of the minor, 37 percent of the moderate, and 75 percent of the severe test cases, the predicted injury outcome is the same as the observed.

Table 1.
Prediction and Model Validation

CASEID	INJURY OUTCOME (OBSERVED)	INJURY OUTCOME (MODEL-PREDICTED)	INTRUSION (centimeters)	ESTIMATED DISTANCE (meters)	QUARTER TURNS	MAXIMUM VERTICAL CRUSH (centimeters)	MATCH (YES/NO)
149009158	Severe	Minor	23	10	2	12	NO
149009923	Severe	Minor	8	15	6	6	NO
149010042	Minor	Minor	10	5	2	3	YES
151009825	Severe	Severe	34	20	3	24	YES
152009795	Minor	Minor	8	5	2	16	YES
155010580	Severe	Severe	44	3	1	0	YES
157010734	Severe	Severe	23	24	5	24	YES
157011096	Severe	Severe	33	22	4	11	YES
157011117	Severe	Severe	21	39	6	10	YES
158009769	Minor	Minor	12	7	2	13	YES
158009949	Moderate	Moderate	20	48	8	20	YES
158010235	Severe	Moderate	14	29	4	26	NO
162010429	Severe	Severe	44	8	3	52	YES
168010870	Minor	Severe	38	5	1	3	NO
169010227	Minor	Minor	7	17	5	9	YES
169010828	Minor	Minor	3	32	6	3	YES
173010473	Severe	Severe	51	1	1	100	YES
173010759	Severe	Moderate	14	27	6	15	NO
174008980	Severe	Severe	9	33	4	8	YES
177010084	Severe	Minor	33	2	1	3	NO
178010042	Severe	Severe	41	9	2	24	YES
178010083	Severe	Moderate	21	66	6	29	NO
178010186	Minor	Moderate	10	27	6	14	NO

Continued

Table 1 (Continued).
Prediction and Model Validation

CASEID	INJURY OUTCOME (OBSERVED)	INJURY OUTCOME (MODEL-PREDICTED)	INTRUSION (centimeters)	ESTIMATED DISTANCE (meters)	QUARTER TURNS	MAXIMUM VERTICAL CRUSH (centimeters)	MATCH (YES/NO)
178010624	Minor	Severe	27	21	6	24	NO
179009371	Moderate	Moderate	15	21	6	15	YES
179010395	Severe	Severe	34	13	2	0	YES
195010789	Severe	Severe	39	32	5	2	YES
195010869	Moderate	Severe	38	13	3	23	NO
195011131	Minor	Minor	7	2	3	5	YES
437009827	Minor	Severe	38	10	6	27	NO
437010089	Severe	Moderate	17	39	8	15	NO
437010267	Severe	Severe	20	39	8	23	YES
437010412	Moderate	Minor	10	8	4	8	NO
511010876	Severe	Severe	22	24	3	0	YES
530004191	Moderate	Severe	18	5	2	17	NO
530004241	Moderate	Severe	53	17	6	51	NO
613009688	Minor	Minor	5	21	4	6	YES
613009887	Severe	Severe	16	18	2	3	YES
613010766	Moderate	Moderate	13	60	8	9	YES
622010137	Severe	Severe	37	18	2	19	YES
720011208	Severe	Severe	45	18	3	18	YES
720011228	Minor	Minor	16	7	2	11	YES
748010659	Severe	Severe	16	7	2	26	YES
762010524	Severe	Severe	15	8	1	13	YES
767011071	Moderate	Severe	38	17	6	30	NO
770011869	Severe	Severe	45	9	2	40	YES
773010863	Severe	Severe	29	8	2	3	YES
778011369	Severe	Severe	25	28	2	5	YES
797005706	Severe	Severe	25	65	8	23	YES
908004479	Minor	Moderate	20	19	3	16	NO
Data source: NASS-CDS (2006-2007)							

Examples: Clinical Analysis of Some NASS-CDS Cases

Matched cases

Example 1. Minor predicted as Minor

Figure 6 shows a "minor" rollover crash that has been predicted as minor by the model, based on the predictors' values: Quarter turns = 2, Estimated distance = 5 meters, Maximum intrusion = 10 centimeters, and Maximum vertical crush = 3 centimeters.

Figure 6. A minor rollover crash predicted as minor- Caseid 149010042 (Source: NASS-CDS).

Example 2. Moderate predicted as Moderate
Figure 7 shows a "moderate" rollover crash that has been predicted as moderate by the model, based on the predictors' values: Quarter turns =8, Estimated distance = 60 meters, Maximum intrusion = 13 centimeters, and Maximum vertical crush = 9 centimeters.

Figure 7. A moderate rollover crash predicted as moderate - Caseid: 613010766 (Source: NASS - CDS).

Example 3. Severe predicted as Severe
Figure 8 shows a "severe" rollover crash that has been predicted as severe by the model, based on the predictors' values: Quarter turns = 8, Estimated distance = 39 meters, Maximum intrusion = 20 centimeters, and Maximum vertical crush = 23 centimeters.

Figure 8. A severe rollover crash predicted as severe- Caseid: 437010267 (Source: NASS-CDS).

Mismatched case:
Example: Figure 9 shows a rollover crash that has been predicted as severe by the model. However, the observed VMAIS of the driver in the case vehicle was minor. In this case the seating position of the driver relative to the maximum intrusion and maximum crush may have influenced the observed injury outcome. As stated earlier, the model predicts the injury outcome based on the crash and vehicle parameters not the occupant location. The model classified the case as severe based on relatively high values: Quarter turns = 6, Estimated distance = 21 meters, Maximum intrusion = 27 centimeters, and Maximum vertical crush = 24 centimeters. The pictures of the damage also indicate a severe rollover.

Figure 9. A rollover crash predicted as severe - Caseid: 178010624 (Source: NASS -CDS).

The model predicted injury outcome appears correct based on the observed severity of damage in terms of the predictors.

DISCUSSION OF RESULTS

One of the measures of rollover crash severity is the injury outcome of the crash. A multidimensional predictive model is developed that uses crash severity surrogates quarter turns, estimated distance, intrusion, and maximum vertical crush to predict the injury outcome in rollovers. These severity surrogates showed positive correlation with the maximum MAIS in the rollover vehicle.

Ninety-one percent of the rollover vehicles in the sample resulted in VMAIS 0-2 injuries. High belt use could have resulted in high counts of minor injuries. The serious and fatal injuries in rollovers are associated with ejections that were not included in the sample. The number of rollover cases in VMAIS 6 group (less than 1%) is too small to sufficiently train the model to correctly predict such cases. As more data becomes available, the model will be able to learn more and acquire greater predictive capability.

The model can be used to classify new rollover cases in NASS-CDS based on their predicted injury outcome. The model-based classification can then be used to identify comparable rollover crashes. The proposed model can also be used as a simulation tool to predict the injury outcome of rollover, given the values of predictors. This can provide guidelines to extract comparable cases to understand injury mechanisms in rollovers that can be used to develop vehicle crashworthiness countermeasures.

A close look at the data shows that severe rollovers, in general, have higher intrusion. Increased intrusion in the vehicle correlates with an increased probability of occupant injury. This suggests that preventing intrusion could prevent serious injuries. The data also shows that an interrupted rollover is likely to result in higher intrusion and vertical crush. Such rollovers are more likely to cause serious injuries to the occupants.

The data used in this study is available through NASS-CDS case viewer on the web at: https://www.nhtsa.gov/portal/site/nhtsa/menuitem.3525b237b7215dd24ec86e10dba046a0/

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