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Identification of characteristics and frequent scenarios of single-vehicle rollover crashes during pre-ballistic phase; part 1 – A descriptive study

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A B S T R A C T

This study aimed to identify common patterns of pre-ballistic vehicle kinematics and roadway characteristics of real-world rollover crashes. Rollover crashes that were enrolled in the National Automotive Sampling System-Crashworthiness Data System (NASS-CDS) between the years 2000 and 2010 were analyzed. A descriptive analysis was performed to understand the characteristics of the pre-ballistic phase. Also, a frequency based pattern analysis was performed using a selection of NASS-CDS variables describing the pre-ballistic vehicle kinematics and roadway characteristics to rank common pathways of rollover crashes. Most case vehicles departed the road due to a loss of control/traction (LOC) (61%). The road departure with LOC was found to be 13.4 times more likely to occur with slippery road conditions compared to dry conditions. The vehicle was typically laterally skidding with yawing prior to a rollover (66%). Most case vehicles tripped over (82%) mostly at roadside/median (69%). The tripping force was applied to the wheels/tires (82%) from the ground (79%). The combination of these six most frequent attributes resulted in the most common scenario, which accounted for 26% of the entire cases. Large proportion of road departure with LOC (61%) implies electronic stability control (ESC) systems being an effective countermeasure for preventing single-vehicle rollover crashes. Furthermore, the correlation between the road departure with LOC and the reduced friction limit suggests the necessity of the performance evaluation of ESC under compromised road surface condition.

1. Introduction

Rollover crashes account for 33% of all motor vehicle occupant fatalities while constituting only 1.7% of the vehicular crashes in the United States (NHTSA, 2016). Also, single-vehicle rollovers accounted for 82.5% of all the rollover crashes (Bose et al., 2011).

Despite a significant number of fatalities from rollover crashes, the most common patterns of rollover crashes are largely unknown in the literature. Parenteau et al. (2003) analyzed the characteristics of rollover crashes regarding the type of rollover and associated corresponding test method, but there was little consideration of the pre-roll behavior (e.g. steering maneuver, loss of control, etc.) of vehicles. While researchers tried to determine the major event pathways that resulted in rollover crashes to estimate the effectiveness of electronic stability control systems in mitigating rollover crashes (Blower et al., 2005) or to develop test methods to evaluate such rollover countermeasures (Viano and Parenteau, 2003), the authors considered limited number of cases. Viner (1995) examined rollover cases, which ranged from around the 1980s to the early 1990s, from the Fatal Accident Reporting System (FARS), the General Estimating System (GES) data, and the Crash Avoidance Rollover Study (CARS). Although the author performed an in-depth analysis of the rollover cases, the most common patterns of single-vehicle rollover crashes were not identified since the individual characteristics of the vehicle, roadway, and driver was analyzed separately instead of grouping these into a common pattern of rollover crashes. The most common pattern of single-vehicle rollover crashes consists of a combination of these common individual rollover characteristics. Also, since the data from these studies are more than a decade old, the vehicles may not be representative of current technology. It is more meaningful and useful to use recent rollover crash data to consider changes in the fleet, roadway, and driver.

Many dynamic rollover crash test methods have been developed to investigate the behavior of a vehicle and an occupant during a rollover crash, but the representativeness of the test conditions is still largely

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unknown. There are laboratory soil and curb trip rollover tests that have considered the pure lateral motion of the vehicle (Chou et al., 2005), but the associated simplification of the vehicle and occupant kinematics were not justified. While a steering induced rollover test using a steering robot (Asay and Woolley, 2010) is potentially one of the most field-relevant rollover test methods, a representative steering input is unknown. Also, this test is not suitable for parametric study because of the repeatability issue in generating similar vehicle kinematics during the test. Controlled dynamic rollover tests, which specify vehicle orientation and kinematics at touchdown, have the potential to improve test repeatability since artificially tripping the vehicle can result in a wide variety of rollover kinematics for the same input (Orlowski et al., 1985). Despite this benefit, such test methods (Cooper et al., 2001; Jordan and Bish, 2005; Kerrigan et al., 2011) require that the combination of test parameters (roll angle, roll rate, vertical velocity, etc.) be realistic, but there is a paucity of information in the literature describing such realistic conditions. Similarly, various vehicle driving tests, which include J-turn, fishhook, sine with dwell, double lane change, etc., have been developed to evaluate the performance of electronic stability control systems (Forkenbrock et al., 2005). Note that these tests more focus on imposing high level of severity on the vehicle and obtaining high repeatability rather than reproducing realistic pre-ballistic vehicle kinematics.

This study aimed to identify common patterns of pre-ballistic vehicle kinematics and the road characteristics of rollover crashes to aid in-depth analysis, computational modeling, and developing physical testing of vehicle rollover. The National Automotive Sampling System-Crashworthiness Data System (NASS-CDS) database was analyzed to investigate the characteristics of pre-roll, or pre-ballistic vehicle kinematics and road environment and to identify the most common patterns of rollover crashes.

2. Method

2.1. Crash data sources and selection criteria

The NASS-CDS database is a publicly available crash data collection program sponsored by the U.S. Department of Transportation (NHTSA, 2011). The NASS-CDS database provides the U.S. representative data regarding motor vehicle crashes based on a weighted annual sample of approximately 5000 police-reported collisions. To be included in the NASS-CDS sample, a crash must involve at least one vehicle that is towed from the scene of the crash. NASS-CDS includes crash reconstructionist or investigator determined detailed information for each single crash, including vehicle properties, damage to the vehicle, crash conditions, occupant characteristics and the injury outcome sustained by each vehicle occupant. For each case enrolled in the NASS-CDS, the crash investigator determines the most harmful event regarding vehicle damage and also attributes the object contacted resulting in this event. The NASS-CDS further specifies the chronological order of the most severe event during the crash.

In the current study, rollover crash cases that were enrolled in the database between the years 2000 and 2010 were included. Single-vehicle rollover crashes were defined as crashes involving only one recorded vehicle with at least one vehicle quarter turn and less or equal to 16 quarter turns (4 roof inversions) in any of the crash events. Vehicle class was filtered to include only passenger cars, sport utility vehicles (SUVs), light trucks, and minivans, with the criterion that their curb weight does not exceed 5000 kg. The selected cases were further filtered to include only those rollovers in which the rollover kinematics of the vehicle were attributed to the most or second most harmful event as the first event of the crash. We restricted our analysis to NASS-CDS occupants greater than 16 years of age with known sex, who were seated in front row left side as a driver. Additionally, cases having zero or negative inflation factors or involving vehicle fire and water submersion or extremely rare occasions (RATWGT $> 10^6$) were excluded from the analysis. Three cases were excluded because the inflation factor equaled zero, and no case was excluded because for having an inflation factor greater than 10^6.

2.2. NASS-CDS variables chosen for descriptive analysis

The NASS variables, which describe the vehicle property, pre-ballistic vehicle kinematics, road characteristics, and driving behavior related properties, were analyzed to understand the characteristics of the pre-ballistic phase in the selected rollover cases (see Table 7 in the Appendix A). Also, odds ratios for accident type and road surface condition were calculated. For this analysis, survey-based frequency estimation was performed using the sampling information and the ratio inflation factor provided in the NASS-CDS associated with each of the sampled cases to predict the frequency estimates at the national level along with the 95% confidence interval limits using the SAS software (Version 9.1.3, SAS Institute Inc., Cary, NC, USA).

Table 1
List of NASS-CDS variables used for rollover crash pattern analysis.

Category	Pattern variables	Permissible values (total number of permissible values)
Vehicle property	Vehicle body category	Car, SUV, pickup, and van (4)
Pre-ballistic kinematics	Accident type	Road departure with loss of control/traction, road departure with drive off the road, road departure with avoiding collision, etc. (5)
	Pre-impact stability	Laterally skidding, longitudinally skidding, tracking, etc. (5)
	Location of rollover	Roadside/median, roadway, shoulder-paved, unpaved shoulder, etc. (5)
	Rollover initiation object	Ground, trees, poles, embankment, etc. (9)
	Location on vehicle where initiation applied	Wheels/tires, non-contact force, etc. (3)
	Rollover initiation type	Trip-over, fall-over, turn-over, and other (4)
Primary roadway characteristics	Speed limit (km/h)	8–49, 56–80, 89 or above, and unknown (4)
	Roadway alignment	Straight and curved (2)
	Roadway surface condition	Dry, slippery (wet/snow/slush/ice/frost), and other (3)
Secondary roadway characteristics	Roadway inclination	Level, uphill grade (> 2%), downhill grade (> 2%), and other (4)
	Roadway surface type	Asphalt/concrete, slag/gravel/stone, dirt, and other (4)
	Number of lanes	1, 2, 3–4, and 5 or more (4)
	Traffic junction information	Non-interchange area and non-junction, interchange area related, intersection related/non-interchange, and other (3)
	Traffic flow information	Not physically divided (two-way traffic)/divided trafficway-median strip without positive barrier, divided trafficway-median strip with positive barrier, etc. (4)