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ABSTRACT

The evaluation of a rollover accident requires the assessment of a large amount of information in order to completely analyze the accident and determine the vehicle dynamics throughout its roll sequence. This information includes the physical evidence available through examination of the accident site, the vehicle and any photographs or documentation of the accident scene.

Many times there is a lack of scene data available complicating a thorough evaluation of the vehicle path and roll distance during the rollover. Inspection of the vehicle reveals the minimum number of rolls the vehicle experienced during the rollover event, leaving the roll distance traveled as one of the many unknown variables.

This paper compares the roll distance, roll speed and number of rolls for dolly testing and real world rollovers. An evaluation of the roll distance and number of rolls for passenger cars, light trucks and sport utility vehicles is compiled and compared to one another. Relationships were found and discussed.

INTRODUCTION

In 1996, rollover accidents accounted for only 2 percent of all vehicular accidents, yet over 18 percent of all fatal accidents were a result of rollovers[1]. The accident reconstruction community has spent much time evaluating these accidents and the mechanisms that cause them. These studies have included the evaluation of rollovers from the standpoint of occupant kinematics, injury mechanisms, restraint system performance, vehicle dynamics, rollover testing and various accident reconstruction techniques. In many of these studies the discussion of number of rolls per roll distance has been a topic, but has not been the main focus of the study.

The reconstruction of a rollover accident includes the evaluation of all phases of the rollover, the pre-trip/tip-up, trip/tip-up and tip-over/rollover phases. The evaluation of the rollover phase in particular, has garnered much attention and many tests have been conducted in attempts to gain valuable insight into this aspect of the rollover accident. The majority of testing and research that has been conducted has involved the use of a dolly to initiate the rollover event. The information that has come from this testing has been vital in the progression of the knowledge of the rollover phenomena. Additionally, it was noted by Orlowski et al.[2] that the evaluation of the dolly tests indicated a higher number of rolls per roll distance than was typically seen in real world rollovers.

The information necessary to thoroughly evaluate a rollover accident is extensive. If the information is obtained correctly and in a timely fashion the accident may be properly analyzed. Any of the accepted techniques for the reconstruction of rollover accidents can be utilized. However in some instances the extent of the data is limited due to actions, which are out of the reconstructionists control. This leads to a more difficult and sometimes limited reconstruction.

In some instances, the physical evidence is limited to an inspection of the subject vehicle involved in the rollover. The evidence available at the scene of the accident has not been recorded or has been recorded improperly. This leaves the vehicle, which in itself can be used to determine the minimum number of rolls experienced throughout the rollover event, as the sole piece of physical evidence. The lack of scene data can lead to unknown variables such as vehicle locations at the time of ground contact, the vehicles final point of rest, the initiation of rollover and the roll distance translated during the rollover phase. At that time alternative methods to determine the roll distance must be used for analysis. Bready et al.[3] discussed in his paper the use of roll distance as an alternative method of analysis to help determine the number of rolls in a rollover event.

The same could be said for the use of the number of rolls being used to determine the roll distance.

This paper incorporates information from reconstructed rollover accidents and dolly testing to compare the roll distance for vehicles involved in the dolly testing to real world rollovers. In addition the information was used to evaluate the roll distance per number of rolls for passenger cars, light trucks and sport utility vehicles. The data was also used to compare the roll distance of the different vehicle classes and the number of rolls to the speed of the vehicle at trip/tip-up, the location of the vehicle relative to the roadway at trip/tip-up and surface the vehicle rolled over.

DATA

There are several factors, which can initiate a rollover sequence. Factors that can lead to on-road friction rollovers are drifting off the edge of a road, collision avoidance, loss of directional stability on a slippery patch of road, collisions that cause a yaw disturbance or tire detread[4]. Other factors, which induce rollovers, are tripping and furrowing in soil. All of these types of rollover mechanisms were encountered and evaluated when gathering data.

The reconstruction of a multiple roll accident is a very complex task due to the variety of parameters that is encountered in each of the rollover accidents. This variety of parameters includes, but is not necessarily limited to the variation in the terrain, the mechanism that initiates the rollover, the geometry of the vehicle, the different objects encountered during roll and the speed of the vehicle at the initiation of rollover. Since the parameters in each rollover event are unique to that event, the differences in the selected reconstructed rollover accidents used for this data were not limited to any of the above mentioned parameters.

Each reconstructed rollover event was evaluated on an individual basis to determine the qualification of that reconstruction. The only considerations used to select a reconstructed rollover event were that the physical evidence was extensive enough to complete a reconstruction using accepted techniques. A thorough reconstruction of the rollover event was completed and the pre-trip/tip-up, trip/tip-up and post-trip/tip-up phases were all analyzed. The speed of the vehicle at initiation of rollover was calculated using the known roll distance and a deceleration factor[7] of 0.48g +/- 10%. The rollover accident was then evaluated for the roll distance, the speed at trip/tip-up, the number of rolls, the surfaces on which it rolled and the surface on which it began its roll sequence.

A reconstructed rollover event was eliminated from the data set if the physical evidence did not allow the determination of the number of rolls or the roll distance. The reconstructed rollover event was also eliminated if an impact initiated the rollover, however if the impact induced a loss of control, which in turn led to the rollover of the vehicle, the reconstruction was used. If the vehicle was contacted at some point in its rollover sequence by an object that impeded the rotational or translational energy, the data was excluded. The characteristics of each of the reconstructed rollover vehicles used in this analysis can be found in table 1 of the appendix.

The rollover tests[5] obtained for evaluation were all dolly tests completed by NHTSA, these can be found in table 2 of the appendix. The Malibu dolly test data, which can be seen in table 3 of the appendix, was obtained through research[6]. These tests were used as the data set for dolly rollover crash tests.

DISCUSSION AND RESULTS

During the analysis, it was determined that only a select number of comparisons would be available for evaluation due to the limited number of reconstructed accident events. The expectations of a large amount of data were quickly trimmed during the gathering of data because of the limited data in the reconstructions, which had been completed. The number of reconstructed rollover accidents began at over 100 and was reduced to the twenty-four that were used in this study.

The data obtained from the dolly rollovers and the data from the reconstructed rollovers, which is found in tables 1,2 and 3 of the appendix, are plotted out into graphs in figures 1-10. The speeds, reported in table 1 and figures 2, 3 and 4 of the reconstructed rollover events were obtained using a deceleration of 0.48g[7]. The data was analyzed to determine if the roll distance was directly related to the number of rolls for vehicles involved in rollover situations. The surface on which the vehicle initiated the rollover and the surface that the rollover event occurred were also evaluated for an influence on the number of rolls of the vehicle and the roll distance. The trip/tip-up velocity was evaluated to determine if, as suggested by Jones et al. [4], it dictates the number of rolls.

RECONSTRUCTED ACCIDENTS

The roll distance for three classes of vehicles, passenger cars, sport utility vehicles and pickup trucks, were compared to one another. Figure 1 shows the results of the number of rolls vs. the roll distance for the reconstructed rollovers. The results show that the roll distance and the number of rolls for the sport utility vehicles are higher than both pickup trucks and passenger cars. This can be due to factors such as the vehicle geometry, the random nature of the rolls and the speed of the vehicle at initiation of rollover. The speed at the initiation of rollover appears to be directly related to these reactions. The results of the roll distance vs. trip/tip-up speed and number of rolls vs. trip/tip-up speed can be seen in figures 2 and 3 respectively. As the speeds of the vehicles at initiation of rollover increase, the roll distance increases proportionally, which is expected since the two variables are directly proportional to one another in the speed loss equation. The number of rolls vs. trip/tip-up speed shows a relationship that appears to be linear even though the two variables are not directly proportional to one another. The relationship of the two is not as directly visible as that seen in the roll distance vs. trip/tip-up speed, however the graph does show a trend in which the increase in speed increases the number of rolls. The variations in the number of rolls can be due to a number of factors such as the vehicle size and configuration, the random nature of rollovers and the deformation of the vehicle as the roll is continued.

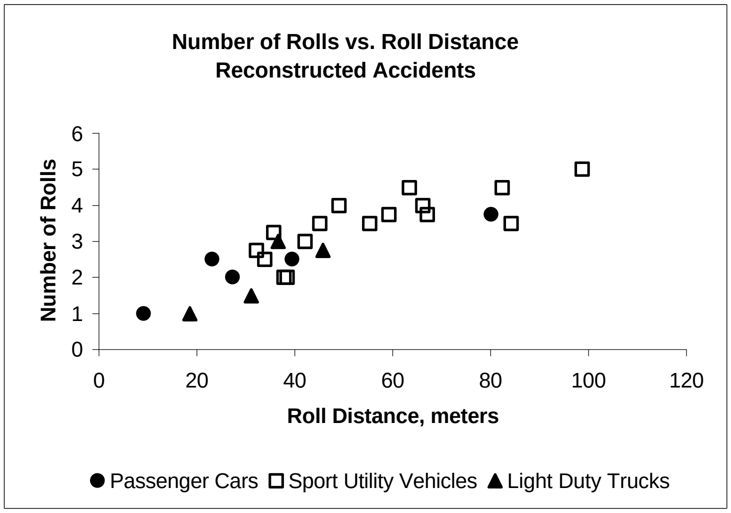

Figure 1. Number of Rolls vs. Roll Distance for the Reconstructed Accidents

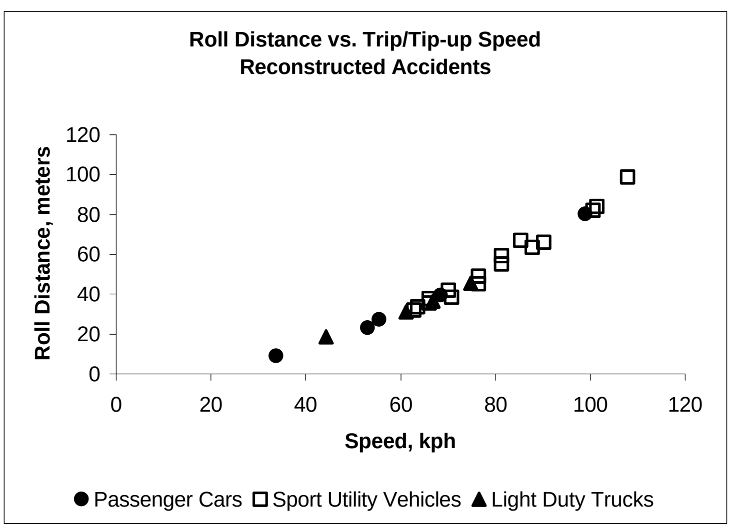

Figure 2. Roll Distance vs. Trip/tip-up Speed for the Reconstructed Accidents

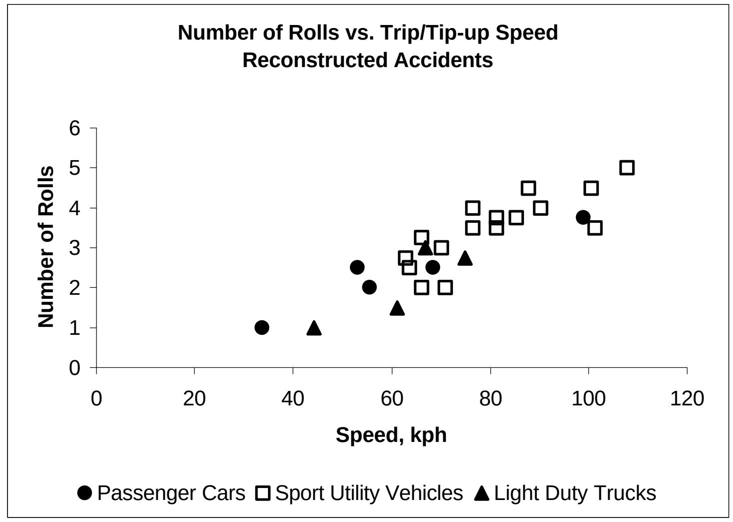

Figure 3. Number of Rolls vs. Trip/tip-up Speed for the Reconstructed Accidents

The range of number of rolls as a function of the roll distance the vehicle traveled can be seen in figure 1. The information in this graph shows that for rollovers where the vehicle rolled one time or less the average roll distance per roll was 14m (45.9ft.). For vehicle paths in which the vehicle rolled from one to two rolls, the average roll distance per roll was 20.7m (67.8ft.). (The information for one to two rolls only involved one rollover and therefore would not be a good basis for determining the roll distance for this range.) For vehicle paths in which the vehicle rolled from two to three rolls, the average roll distance per roll was 16.9m (55.4ft.). For vehicle paths in which the vehicle rolled from three to four rolls, the average roll distance per roll was 16.1m (52.8ft.). Finally for situations in which the vehicles rolled more than four times, the average roll distance per roll was 16.1m (52.8ft.). This shows that as the roll progresses the average roll distance for each roll does not greatly increase. In addition, toward the end of the rollover sequence the average roll distance per roll slightly decreases.

The information in figure 4 shows the relationship between the number of rolls and trip/tip-up speed as a function of where the rollover sequence initiated. The vehicles that began their rollover sequence on road tended to be traveling at a higher velocity than those vehicles which began to roll off road. The majority of the vehicles that began to roll on the road were sport utility vehicles that had not dissipated significant energy during their pre-trip/tip-up phase. The vehicles traveling at higher speeds at the time they began to roll off road were also sport utility vehicles, which once again had not dissipated significant energy prior to the initiation of rollover and prior to entering the shoulder. This is due to the lower yaw angle at which the sport utility vehicles began their rollover phase.

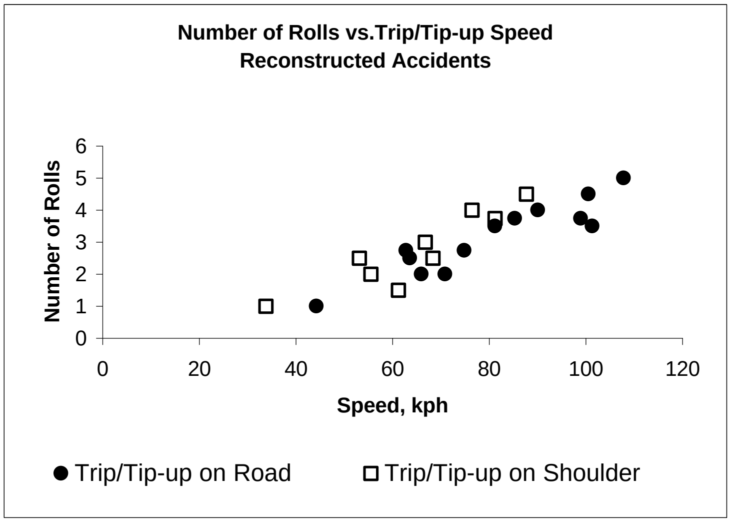

Figure 4. Comparison of location for initiation of rollover for the Reconstructed Accidents

DOLLY ROLLOVER TESTING

The evaluation of the dolly tests that were available included passenger cars, sport utility vehicles, pickup trucks/vans and the Chevrolet Malibu. Figure 5 shows the results of the number of rolls vs. the roll distance for all the dolly tests. The results show that the roll distance and the number of rolls is not a linear relationship. Moreover, no relationship exits between the number of rolls and roll distance for the dolly tests.

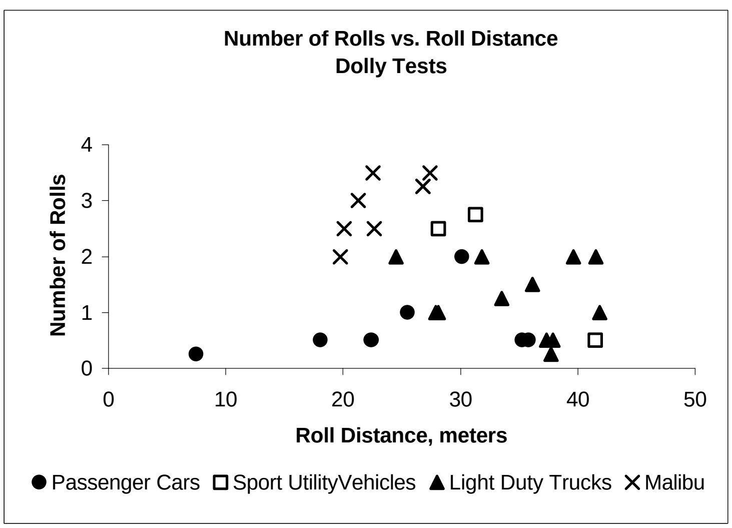

Figure 5. Number of Rolls vs. Roll Distance for All Dolly Tests

The results of the dolly tests for the roll distance vs. trip/tip-up speed can be seen in figure 6. Due to the direct proportionality of the trip/tip-up speed and the roll distance in the speed loss equation the two variables should increase proportionally. However, the results show that instead of the roll distance increasing proportionally as the speed at trip/tip-up increases, the trip/tip-up speed remains the same as the roll distance increases. Therefore, the roll distance is not a function of trip/tip-up speed for the dolly tests. Figure 7 shows a similar relationship for the number of rolls vs. trip/tip-up speed for the dolly tests. Again, no relationship between number of rolls and trip/tip-up speed exits for the dolly tests.

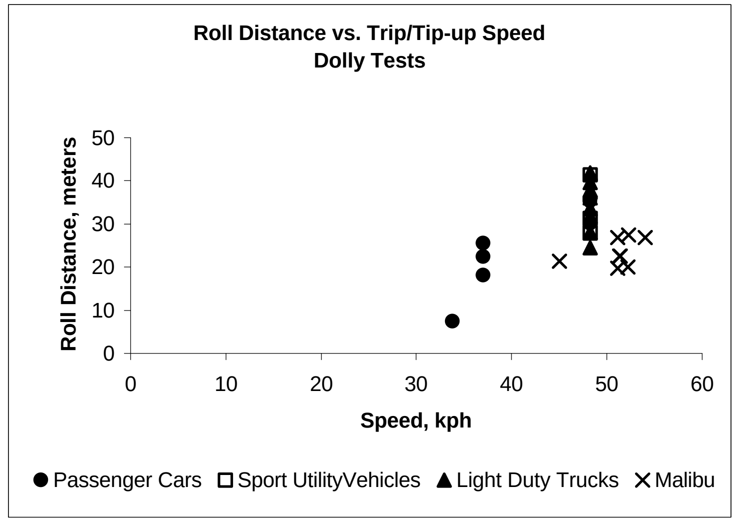

Figure 6. Roll Distance vs. Trip/tip-up Speed for All Dolly Tests

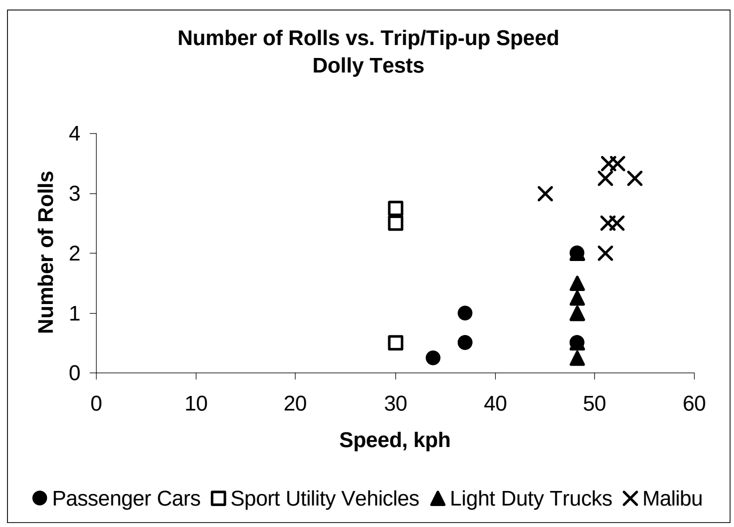

Figure 7. Number of Rolls vs. Trip/tip-up Speed for All Dolly Tests

The graph for the number of rolls for the dolly testing as a function of the roll distance can be seen in figure 5. From the information in this graph we can determine that in rollovers in which the vehicle rolled one time or less, the average roll distance per roll was 58m (190.9ft.). The vehicles that rolled between one and two rolls traveled an average distance per roll of 22.3m (73.2ft.). The average roll distance per roll for the vehicles in the dolly tests that rolled between two and three rolls was 9.9m (32.5ft.). For vehicle paths in which the vehicle rolled over three rolls, the average roll distance per roll was 7.7m (25.1ft.). This shows no useful correlation exists for the dolly tests for use as a comparison of the roll distance as the number of rolls increases.

RESULTS COMPARISON

A comparison of the reconstructed rollover accidents and dolly tests is shown in figures 8, 9 and 10. The comparison of the number of rolls vs. the roll distance, seen in figure 8 reveals that the roll distance for the reconstructed accidents showed a much lower average roll distance per roll for the range of zero to one roll. This was due to the fact that many of the dolly tests did not roll more than one time and many of them much less than one roll. This lead to much of the translational distance of the dolly tests which rolled less than one time sliding on one of their sides or on the roof. Once the dolly rollovers tumbled more than one revolution, the testing showed that the roll distance per roll was considerably less than the reconstructed rollover accidents

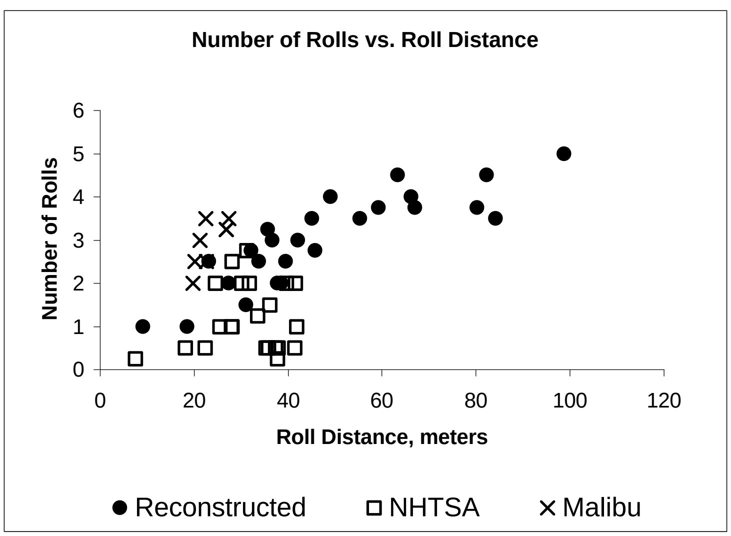

Figure 8. Number of Rolls vs. Roll Distance for Reconstructed Accidents and All Dolly Tests

The data in figure 9, which includes a deceleration range of +/- 10%, shows the difference in distribution for the roll distance in relationship to the speed at trip/tip-up for both the reconstructed rollovers and the dolly testing. The roll distance for the dolly testing does not increase proportionally as the reconstructed rollover accidents did as the speed at trip/tip-up increased. The relationship between the roll distance and the speed at trip/tip-up should show a direct relationship to one another as is seen in the reconstructed rollovers, not in the dolly testing.

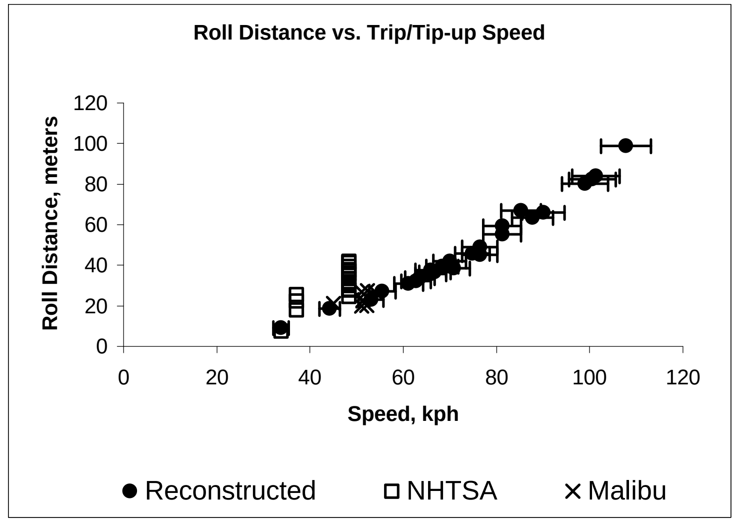

Figure 9. Roll Distance vs. Trip/tip-up Speed for Reconstructed Accidents and All Dolly Tests

The information revealed in figure 10 shows the relationship between the number of rolls and the speed of the vehicle at trip/tip-up. As can be seen in the reconstructed rollover data, there appears to be a relationship, while the dolly tests are localized in one area. The possible reasons for the discrepancies between the reconstructed rollovers and the dolly tests may be attributed to a lower number of varying factors leading up to the initiation of rollover for dolly tests than reconstructed rollovers. Factors such as yaw velocity and furrowing were not encountered during dolly testing.

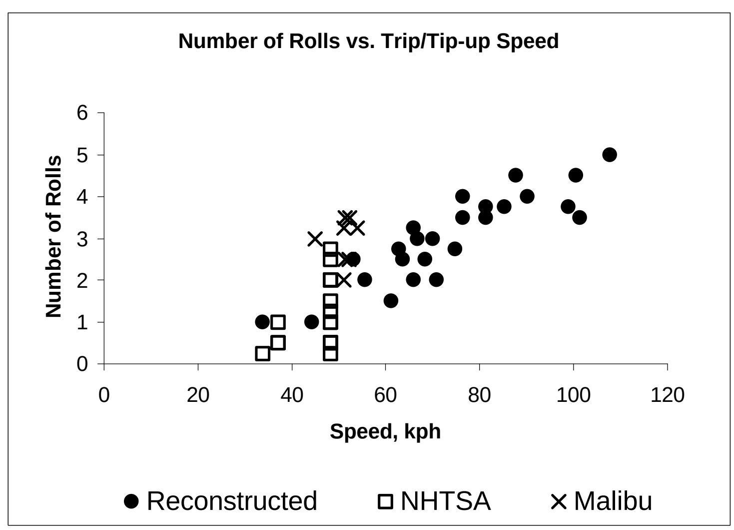

Figure 10. Number of Rolls vs. Trip/tip-up Speed for Reconstructed Accidents and All Dolly Tests

CONCLUSIONS

1. The results of this study for the reconstructed accidents illustrate the expected non-linear relationship between the speed of the vehicle at trip/tip-up and the roll distance. In addition a direct relationship can be seen between the speed of the vehicle at trip/tip-up and the number of rolls. This leads to the number of rolls of the vehicle being directly related to the roll distance.

2. The average roll distance per roll for vehicles that roll one time or less is approximately 14m (45.9ft.). The average roll distance per roll for vehicles that roll more than two times is constant between 16.1m (52.8ft.) and 16.9m (55.4ft.). These values for average roll distance are much greater for the reconstructed rollovers than for the dolly tests.

3. It was observed that the speed of SUV's at trip/tip-up was on average higher than the other vehicle classes probably due to the lower yaw angle at initiation of rollover.

4. The use of dolly tests to relate roll distance, trip/tip-up speed, and number of rolls is not an effective tool for use in rollover accident reconstruction.

5. The relationship between roll distance, trip/tip-up speed, and number of rolls observed were not affected by the trip/roll surface for reconstructed rollover accidents.

RECOMENDATIONS

1. The addition of reconstructed rollover accidents to this data would be advantageous for future statistical analysis relating roll distance, trip/tip-up speed, and number of rolls.

2. The further analysis of this data could be used to evaluate the roll velocity as a function of roll distance, trip/tip-up speed, and number of rolls.

ACKNOWLEDGMENTS

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APPENDIX

Table 1. Description of Reconstructed Rollover Vehicle Accidents

Vehicle Type	Roll Surface	Trip/tip-up Mechanism	Speed at Trip/tip-up		Roll Distance		Number of Rolls
1991 Subaru Legacy (P)	Combination	Road	61 mph	99 kph	263 ft	80 m	3.75
1993 Mazda Protégé (P)	Shoulder	Shoulder	21 mph	34 kph	30 ft	9 m	1.00
1996 Toyota Corolla (P)	Shoulder	Shoulder	33 mph	53 kph	76 ft	23 m	2.50
1996 Honda Accord EX (P)	Shoulder	Shoulder	34 mph	56 kph	90 ft	27 m	2.00
1995 Isuzu Rodeo (S)	Road	Road	50 mph	81 kph	181 ft	55 m	3.50
1995 Isuzu Rodeo (S)	Combination	Road	67 mph	108 kph	324 ft	99 m	5.00
1995 Toyota 4-Runner (S)	Road	Road	53 mph	85 kph	220 ft	67 m	3.75
1998 Toyota 4-Runner (S)	Combination	Road	41 mph	66 kph	117 ft	36 m	3.25
1997 Toyota 4-Runner (S)	Combination	Road	41 mph	66 kph	124 ft	38 m	2.00
1994 Suzuki Sidekick (S)	Road	Road	44 mph	71 kph	126 ft	38 m	2.00
1997 Chevrolet Blazer (S)	Shoulder	Shoulder	50 mph	81 kph	194 ft	59 m	3.75
1994 Jeep Cherokee (S)	Combination	Road	39 mph	63 kph	111 ft	34 m	2.50
1993 Ford Explorer (S)	Combination	Road	39 mph	63 kph	106 ft	32 m	2.75
1999 Ford Explorer (S)	Combination	Road	63 mph	101 kph	276 ft	84 m	3.50
1996 Ford Explorer (S)	Shoulder	Shoulder	47 mph	76 kph	148 ft	45 m	3.50
1997 Ford Explorer (S)	Shoulder	Shoulder	47 mph	76 kph	161 ft	49 m	4.00
1995 Ford Explorer (S)	Combination	Road	62 mph	100 kph	270 ft	82 m	4.50
1996 Ford Explorer (S)	Shoulder	Shoulder	54 mph	88 kph	208 ft	63 m	4.50
1993 Ford Explorer (S)	Combination	Road	56 mph	90 kph	217 ft	66 m	4.00
1998 Ford Explorer (S)	Combination	Combination	43 mph	70 kph	138 ft	42 m	3.00
1993 Pontiac Transport SE (T)	Shoulder	Shoulder	42 mph	68 kph	129 ft	39 m	2.50
1986 Toyota 4x4 Pickup (T)	Combination	Road	27 mph	44 kph	61 ft	19 m	1.00
1995 Mazda B-3000 Pickup (T)	Shoulder	Shoulder	41 mph	67 kph	120 ft	37 m	3.00
1988 Ford Ranger 4x4 Pickup (T)	Road	Road	46 mph	75 kph	150 ft	46 m	2.75
1979 C-10 Pickup (T)	Shoulder	Shoulder	38 mph	61 kph	102 ft	31 m	1.50

*Note: (P) Denotes Passenger Car, (S) Denotes SUV, (T) Denotes Light Duty Truck

Table 2. Description of Dolly Tests Conducted by NHTSA

Vehicle Type	NHTSA Test No.	Trip/tip-up Mechanism	Speed at Trip/tip-up		Roll Distance		Number of Rolls
1982 Mercury Zephyr (P)	939	Dolly	23 mph	37 kph	59 ft	18 m	0.50
1979 Dodge Omni (P)	920	Dolly	23 mph	37 kph	73 ft	22 m	0.50
1989 Pontiac Grand Am (P)	1395	Dolly	30 mph	48 kph	117 ft	36 m	0.50
1989 Dodge Colt (P)	1471	Dolly	30 mph	48 kph	116 ft	35 m	0.50
1991 Volvo (P)	1852	Dolly	30 mph	48 kph	99 ft	30 m	2.00
1984 Honda Accord (P)	878	Dolly	21 mph	34 kph	24 ft	7 m	0.25
1982 Chevrolet Celebrity (P)	888	Dolly	23 mph	37 kph	83 ft	25 m	1.00
1988 Ford BroncoII (S)	1255	Dolly	30 mph	48 kph	136 ft	41 m	0.50
1994 Ford Explorer (S)	2514	Dolly	30 mph	48 kph	102 ft	31 m	2.75
1993 Ford Explorer (S)	2553	Dolly	30 mph	48 kph	92 ft	28 m	2.50
1988 Dodge Caravan (T)	1266	Dolly	30 mph	48 kph	124 ft	38 m	0.25
1989 Dodge Caravan (T)	1391	Dolly	30 mph	48 kph	130 ft	40 m	2.00
1988 Nissan Pickup (T)	1274	Dolly	30 mph	48 kph	110 ft	33 m	1.25
1989 Nissan Pickup (T)	1289	Dolly	30 mph	48 kph	122 ft	37 m	0.50
1989 Nissan Pickup (T)	1393	Dolly	30 mph	48 kph	137 ft	42 m	1.00
1989 Nissan Pickup (T)	1394	Dolly	30 mph	48 kph	91 ft	28 m	1.00
1989 Nissan Pickup (T)	2270	Dolly	30 mph	48 kph	104 ft	32 m	2.00
1990 Nissan Pickup (T)	1925	Dolly	30 mph	48 kph	80 ft	24 m	2.00
1990 Nissan Pickup (T)	1929	Dolly	30 mph	48 kph	118 ft	36 m	1.50
1990 Nissan Pickup (T)	2141	Dolly	30 mph	48 kph	136 ft	41 m	2.00
1988 Ford Ranger Pickup (T)	1520	Dolly	30 mph	48 kph	124 ft	38 m	0.50
1988 Dodge Ram 50 Pickup (T)	1521	Dolly	30 mph	48 kph	92 ft	28 m	1.00

*Note: (P) Denotes Passenger Car, (S) Denotes SUV, (T) Denotes Light Duty Truck

Table 3. Description of Chevy Malibu Dolly Tests

Vehicle Type	Trip/tip-up Mechanism	Speed at Trip/tip-up	Roll Distance	Number of Rolls
1983 Chevrolet Malibu (P)	Dolly	52 kph	20 m	2.50
1983 Chevrolet Malibu (P)	Dolly	54 kph	27 m	3.25
1983 Chevrolet Malibu (P)	Dolly	52 kph	27 m	3.50
1983 Chevrolet Malibu (P)	Dolly	51 kph	27 m	3.25
1983 Chevrolet Malibu (cage) (P)	Dolly	51 kph	22 m	3.50
1983 Chevrolet Malibu (cage) (P)	Dolly	45 kph	21 m	3.00
1983 Chevrolet Malibu (cage) (P)	Dolly	51 kph	20 m	2.00
1983 Chevrolet Malibu (cage) (P)	Dolly	51 kph	23 m	2.50

*Note: (P) Denotes Passenger Car, (S) Denotes SUV, (T) Denotes Light Duty Truck