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FACTORS LEADING TO CABLE MEDIAN BARRIER FAILURES

PRZYCZYNY AWARII KABLOWYCH BARIER DROGOWYCH ROZDZIELAJĄCYCH KIERUNKI RUCHU

Abstract Cable median barriers are used across the globe to separate opposing lanes of travel on high-speed and high-volume facilities. In the United States (US) these barriers are frequently used in depressed medians where cross slopes preclude the implementation of most guardrails and all concrete barriers. The ability to install cable barriers on moderate slopes makes them much less costly than other types of barriers. In fact, the simple cost of filling in a median to reduce cross slopes is often more costly than the entire cable barrier system.

Streszczenie Kablowe bariery używane są na całym świecie do rozdzielenia pasm ruchu w przeciwnych kierunkach na drogach o szybkim ruchu i dużym nasileniu. W USA takie bariery są często stosowane w zagłębieniach, gdy spadek zbocza wyklucza zastosowanie większości innych barier a zwłaszcza betonowych. Możliwość zainstalowania kablowych barier na średnio stromych zboczach pozwala na obniżenie kosztów. Praktycznie koszt wypełnienia rowu żeby zmniejszyć kąt nachylenia zbocza jest często dużo większy od całego kosztu bariery kablowej.

General

Cable median barriers have been shown to reduce median related fatal crashes by as much as 90%. Further, accident analysis has shown that for most rural freeways, cable median barriers are the only cost-effective method for controlling cross median crashes. Practical guidelines for the implementation of these barriers in rural areas have been developed and are now beginning to gain acceptance across the US.

However, high speeds and high-traffic volumes commonly found on rural interstate highways across the US produce large numbers of cross median and barrier related fatalities even when a cable barrier is present. It is estimated that more than 250 cross median and cable barrier related fatal crashes occur annually where cable median barrier is installed. Further, industry experts estimate that the installed base of cable median barriers in the US will double over the next 10 years. Such an increase in cable barrier installations could be expected to produce 500 barrier related fatal crashes per year. Unfortunately there currently is no information available that indicates why some vehicles penetrate through or rollover during cable barrier crashes. Thus, there is a need to identify factors that lead to serious injury and fatal crashes involving cable median barriers. Identifying the characteristics of these costly crashes is the first step in the process of improving barrier designs to minimize the overall accident costs associated with these barriers.

In recognition of the need to improve the safety performance of cable median barriers, the Mid-America Transportation Center funded a study of cable median barrier failures.

The study focused on serious injury and fatal crashes involving cable median barriers and started with the collection of more than 20,000 cable barrier related accident records. This database was reduced to approximately 500 crashes (2.5%) that involved either serious or fatal injuries to one of the vehicle occupants. The data set was further restricted by lack of adequate trajectory data to approximately 1900 crashes. Vehicle types, impact angles, vehicle orientation, and median configuration were compiled for each of the serious injury and fatal crashes. A similar database was developed under a separate study that provided detailed information regarding impact conditions for serious injury and fatal ran-off-road crashes on high-speed freeways.

Comparison of the two distributions of vehicle types and crash conditions has identified a number of critical impact conditions and median configurations that were significantly overrepresented in the cable barrier crash database. These crash parameters can now be utilized by barrier designers to isolate common causes for vehicle penetration of cable barriers and/or vehicle rollovers associated with cable barrier crashes. Based on an evaluation of the common crash conditions associated with barrier penetrations it is anticipated that serious injury and fatal crashes involving cable median barriers can be reduced by as much as 30% by redesigning cable barriers to eliminate this problem. Even this modest level of improved safety performance could eventually eliminate as many as 150 fatal crashes each year across the United States.

Many roadways with divided medians and high traffic volumes are subject to a high risk of crossover crashes. Cable median barriers are a safe, effective, and inexpensive method of preventing these crossover crashes. Cable median barriers have been shown to reduce median related fatal crashes by as much as 90% (1). Further, accident analysis has shown that for most rural freeways, cable median barriers are the only cost-effective method for controlling cross median crashes (2). Practical guidelines for the implementation of these barriers in rural areas have been developed and are now beginning to gain acceptance across the US (2).

Although cable median barriers generally show exceptional crashworthiness behavior and have exceeded the design capacity in many crash events, cable median barriers are still subject to vehicular penetration and rollovers, frequently resulting in incapacitating injury or fatality. At the same time, cable median barrier construction continues to increase, and many industry experts predict that the installed base of cable median barrier will double in the United States in the next decade. Researchers are at a unique position to identify potential problems and causes of cable median barrier failures before the barriers are installed, and may therefore prevent as many as 250 fatalities resulting from crashes with cable median barriers every year

Introduction

Much of the US freeway system was designed and constructed in the 1950s and ‘60s. During this time it was common to build high-speed facilities with 9 m (30 ft) and 12 m (40 ft) wide open medians. However, with low traffic volumes found on those freeways during this period, frequency of tragic cross median crashes was still relatively low. The California Department of Transportation, (Caltrans), conducted a study on the benefits of using cable barrier in these relatively narrow medians (4). This study indicated that barriers could not be justified in medians wider than 15 m (50 feet). Caltrans repeated this study several times between 1973 and 1993. Each time the authors arrived at the same conclusion, barriers were not cost-effective when installed in medians wider than 50 feet. However, findings from the 1997 version of this study were quite different and recommended barriers be placed in medians as wide as 22 m (75 ft) (5).

Cable barriers have long been recognized as an effective way of preventing vehicles from encountering dangerous side slopes and embankments and separating traffic on high-speed facilities. Accident data analysis has indicated that cable barriers provide the highest overall level of safety when compared to concrete safety shapes and steel beam guardrails (6, 7). Further, study of guardrail performance on slopes indicated that cable median barriers can perform effectively when installed on slopes as steep as 5:1 (8) while metal beam guardrails demonstrated unsafe performance on 6:1 slopes. Finally, cable barriers offer the lowest cost barrier option for use in medians of high-speed freeways. In view of the positive safety performance, capability of performing when installed on sloping medians, and low construction costs, is not surprising that most highway agencies in the US have decided to implement cable barriers whenever it is necessary to retrofit an existing depressed median to prevent cross median crashes. As of today more than 30 states departments of transportation has adopted this policy with many of them having installed more than 100 miles barrier. As a result, industry experts begun to predict that the installed base of cable median barrier in the US will more than double over the next 10 years.

Even though cable median barrier has compiled positive performance record, the high number of crashes that occur in narrow medians on high-speed high-volume freeways still produce significant numbers of serious injury and fatal crashes involving cable barrier. A study of more than 5000 cable barrier crashes over a two-year period found 12 fatal and 25 serious injury crashes (1). Surprisingly only half of the fatal crashes involved vehicles penetrating through the barrier and entering opposing traffic lanes. The remaining fatalities appeared to be related impact with the cable barrier. Although, the rate of six fatal crashes per year represented a 90% reduction in fatal crash rates when compared to the time prior to installation of cable barrier, these six fatal crashes per year would indicate that as many as 500 fatal crashes will occur annually in the US when the installed base of cable median barriers doubles over the next decade. This level of fatal crashes associated with any safety feature is unacceptable. If this situation is to be avoided, improved cable barrier designs and deployment guidelines must be developed immediately in order to be implemented during the current wave barrier construction. The first step in developing better barrier designs and placement guidelines is to discover the primary causes associated with cable barrier crashes adducing fatalities and serious injuries.

In recognition of the critical need for better understanding of the causes of cable barrier penetrations and serious injury and fatal crashes, the Mid-America transportation center, in collaboration with Safence Incorporated, funded the study described herein. The goal of this study was to take the first step toward improving cable median barrier performance by determining the factors, such as impact conditions, vehicle type, median slope, and barrier placement that tend to produce cable barrier penetrations and serious injury and fatal crashes. Safence, Mid-America Transportation Center and the Midwest Roadside Safety Facility will utilize the findings from this study to develop a better barrier design and guidelines for barrier implementation that can significantly reduce serious injury and fatal crash rates involving cable median barrier.

Accident Data

The primary source of accident data used in the current study was a collection of crash reports and investigations involving serious injury and fatal crashes on cable median barrier in the State of Missouri. Between 2007 and 2009, 7093 cable median barrier crashes were reported in Missouri, and of those crashes, 174 were recorded as involving serious injury or fatality. Hence the combined serious injury and fatal crash rate for cable barrier in Missouri was found to be 2.5%. This finding is consistent with prior accident studies of cable barriers that indicated low crash severities for cable barriers when compared to other types of barriers. For example, the combined serious and fatal injury rates for guardrail and bridge rail crashes in Kansas were found to be 4.9% and 3.6% respectively (3).

Accident reports were obtained for all 174 crashes involving serious or fatal injury in the Missouri database. Fortunately, 169 of the accident reports included detailed drawings of the accident scene, including measurements of vehicle position near points of departure and impact, and vehicle tire marks laid down as the vehicle approached the barrier. A careful examination of these crashes revealed that the cable barrier had a significant contribution to occupant injury in 128 of the crashes. The remaining 47 crashes involved other mechanisms for occupant injury, including vehicle rollover prior to the barrier impact, impacts with another vehicle before leaving the travelway, and acute health problems unrelated to the crash. When crashes involving injuries produced prior to striking a barrier are eliminated from the database, the combined serious and fatal injury crash rate was reduced to 1.7%.

Note that it is possible that a number of critical injury and fatal crashes involving cable median barriers were incorrectly coded and therefore excluded from the database. However, prior experience with accident reports associated with barrier crashes would indicate that it is not common that a police officer fails to indicate the barrier was struck for an accident involving serious injuries and fatalities. Therefore, the authors assume that the numbers of these crashes missing from the database would be relatively low. Further, even if a significant number of these cases do occur, there is no reason to believe that omitted cases would have a bias in any characteristic other than injury severity. Because police officers likely to spend more time investigating serious injury and fatal crashes, the bias would reduce the risk of case omission as the severity increased.

Using reported length and width measurements taken by investigating officers at points of vehicle departure from the road and impact with the cable median barrier, accident scene diagrams were scaled to account for varying longitudinal and lateral scale factors. Approximate scaled crash scenes were thereby used to generate vehicle trajectory information up to the point of impact with the barrier system. Trajectory data included the vehicle velocity vector angle as well as sideslip angle and the angle between the vehicle's longitudinal axis and the barrier. This information was used to build a database of crash impact conditions to evaluate vehicle/barrier interaction. Unfortunately, the 22 North Carolina crashes utilized different selection criteria than the Missouri cases. Evaluation of the distribution of trajectory angles and heading angles at impact showed that these two datasets were statistically dissimilar. The following two sections of the paper were therefore limited to analysis of the larger Missouri dataset. A subsequent section of the paper compared the two data sets.

Barrier Related Rollovers and Penetrations

As shown in Table 1, rollovers caused by impact with a cable barrier were frequently observed in sedan, pickup, and SUV crashes, which combined for more than 65% of all rollovers observed. By contrast, penetration events commonly involved sedan and coupe impacts. Conventional automobiles accounted for approximately 57% of all cable barrier penetrations. Tractor semi-trailers comprised 13% of the penetration crashes resulting in critical injuries and fatalities. This finding indicates that in order to truly minimize the number of injuries and fatalities associated with cable median barriers and cross median crashes, hardware designers need to develop barriers that can consistently contain large tractor-trailer vehicles.

Table 1. Rollover and Penetration Distributions

Vehicle Type	Rollover		Penetration		Rollover and Penetration	
	Number	Percent	Number	Percent	Number	Percent
Coupe	5	10%	10	20%	4	18%
Hatchback	0	–	2	4%	0	–
Sedan	12	23%	19	37%	7	32%
Wagon	5	10%	3	6%	3	14%
SUV	14	27%	2	4%	2	9%
Pickup	8	15%	7	14%	3	14%
Van	3	6%	1	2%	0	–
Tractor-Trailer	5	10%	7	14%	3	14%
Sum	52	100%	51	100%	22	100%

When impact conditions were examined for crashes involving rollovers or barrier penetration, shown in Table 2, the average angle of impact with the cable barrier was found to be 22°. When tractor-trailer units were excluded from the analysis, the average impact angle for passenger vehicles was found to be 26 degrees. This average impact angle for crashes involving cable barrier failure is much higher than the 16 degree average impact angle associated with serious injury and fatal guardrail crashes that were reported in NCHRP Report 665.

Table 2. Velocity Vector at Impact by Vehicle Class

Vehicle Body Type	Rollover-Only				Penetration-Only				Rollover Plus Penetration			
	Crashes	Average	Max	Min	Crashes	Average	Max	Min	Crashes	Average	Max	Min
Passenger Car	8	26	42	5	20	25	86	4	14	26	54	7
Coupe	1	30	30	30	6	22	35	6	4	27	50	11
Hatchback	0	–	–	–	2	61	86	37	0	–	–	–
Sedan	5	32	42	5	12	21	46	4	7	25	39	7
Wagon	2	10	10	9	0	–	–	–	3	28	54	10
Light Truck/Utility	20	22	56	5	5	47	90	5	5	17	39	8
SUV	12	17	26	5	0	–	–	–	2	12	17	8
Pickup	5	36	56	15	4	58	90	39	3	20	39	8
Van	3	23	34	12	1	5	5	5	0	–	–	–
Tractor-Trailer	2	4	7	1	4	18	29	8	3	10	20	5
Summary	30	22	–	–	29	28	–	–	22	22	–	–

Clearly the safety performance of cable median barriers is more sensitive to impact angle then are other barrier systems. The 26° average impact angle for cable barrier penetration and rollover crashes is particularly significant because current crashworthiness evaluation criteria found in the Manual for Assessing Safety Hardware (MASH) require barrier systems to be tested at no more than 25 degrees (9). European crash testing standards, published under EN-1317, utilize a maximum impact angle of only 20 degrees (10). Thus, roughly half of the cable barrier crashes that could be classified as a barrier failure involved impact angles greater than any crash test contained in the US or EU safety performance guidelines. Based upon the impact angles associated with cable barrier penetration and rollover crashes, it is clear that, if the safety performance of cable barriers is to be materially improved, they must be subjected to higher impact angles during the evaluation process.

However, it should be noted that roughly half of the cable barrier crashes that could be considered a failure involved impact angles within the normal range for crash testing. The effects of vehicle heading angle at impact with the barrier may be an explanation for these failures. As summarized in Table 3, the average vehicle heading angle at impact for crashes involving rollover and penetration was found to be 42 and 36° respectively. In both cases, vehicles were steered into the barrier, meaning the drivers lose control as they steer toward the median. This situation can arise from avoidance maneuvers in the travelway or oversteering in an attempt to recover from an excursion onto outside shoulder.

Table 3. Velocity Vector, Heading, and Sideslip Angles by Vehicle Type

Vehicle Body Type	All Rollover Crashes			All Penetration Crashes			Rollover+Penetration Crashes		
	Velocity Vector	Heading	Sideslip	Velocity Vector	Heading	Sideslip	Velocity Vector	Heading	Sideslip
Coupe	28	89	48	24	40	37	27	107	57
Hatchback	–	–	–	61	104	44	–	–	–
Sedan	28	37	25	23	21	21	25	32	21
Wagon	21	30	12	28	45	17	28	45	17
SUV	16	22	19	12	27	17	12	27	17
Pickup	29	64	34	41	67	29	20	57	37
Van	23	107	55	–	–	–	–	–	–
Tractor-Trailer	8	9	8	13	19	6	10	17	7
Average	22	42	25	26	36	24	23	30	20

Vehicle impact conditions in which the heading angle is not the same as the trajectory angle involve nontracking vehicles. Nontracking refers to a situation wherein the rear wheels do not follow behind the vehicle's front tires. An overall evaluation of the highest severity crash types revealed that the most common impact conditions involved moderately high trajectory angles (between 20 and 30 degrees) but sliding such that the vehicle contacted the barrier with a much more head-on orientation. This type of impact condition was most commonly associated with vehicles having a shallower frontal profile such as sedans, coupes, and hatchbacks. It is theorized that the sloped frontal structure on these vehicles produces a vertical prying action that forces the cables apart and allows the vehicle to penetrate through the system. Vehicles with a deeper front profile such as pickups, and SUVs appear to be more likely to override cable system. However, this behavior is observed most often with cable barrier systems that are 27 inches tall or less. Although raising the top cable seems to be effective at preventing barrier overrides, the accident data still indicates that these barriers can cause higher CG vehicles such as light trucks to roll over.

Findings from a study of median barrier warrants in Kansas was compared to accident data in this study to determine if the rate of barrier penetration was related to the surface condition of the roadway. As shown in Fig. 22, distributions of cross-median excursions and crashes in Kansas and the distribution of cable median barrier penetrations in Missouri were plotted. Roadways were wet when cable median barriers failed to retain vehicles on the traffic side in Missouri in 18% of crashes, which is comparable to the rate of cross-median excursions and crashes in Kansas. However, barrier penetrations occurred much less frequently in icy conditions than in dry conditions in Missouri, while 27% of all cross-median excursions and 37% of all cross-median crashes occurred in icy conditions in Kansas.

Roadway surface conditions affect both vehicle steering capacity and average travel speed on roadways. During rainy conditions, vehicles tend to drive more slowly; but when weather conditions are not inclement but roadways are still wet, travel speeds quickly resume to npormal. However, on wet roadways, tire-surface friction is decreased. This leads to the slight increase in the number of wet roadway-related median barrier penetrations in Missouri.

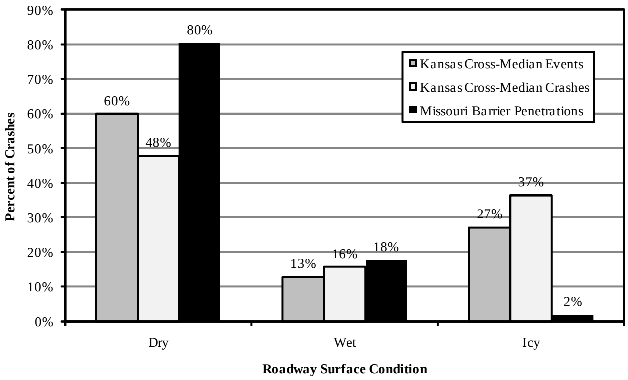

Fig. 22. Roadway Surface Condition Dependence on Roadway Departure

However, when snow or ice was present on the roads, the frequency of cross-median crashes in Missouri was reduced, despite the fact the total number of cable median barrier crashes increased. Because Kansas and Missouri are adjacent states at nearly the same latitude, weather conditions in the states are typically very similar. These findings reinforce the assertions that cable barrier performance is heavily dependent on a combination of vehicle impact speed, velocity vector angle, and vehicle impact orientation. As a result, cable median barrier penetrations would be more likely in states with lower snowfall and higher travel speeds, while penetrations may be less likely in states with colder, icy winters and lower travel speeds.

Crash Severity

Table 4 shows the distribution of crash severity by crash outcome. The most important observation from this table is that the cable barrier itself was responsible for many of the serious injury and fatal crashes. In fact, 64.9% of all serious and fatal injury crashes were associated with vehicles that did not penetrate the barrier. Further, 38% of the fatal and serious injury crashes involved more or less successful barrier behavior wherein the vehicle was contained and remained upright during the crash event. Further, the average and 85th percentile impact angle for these crashes was found to be 16.5 and 25 degrees respectively, both of which are similar to crash data for all ran-off-road crashes (3). A review of accident forms did not identify any common causes of these serious injuries. A more thorough investigation of these crashes is warranted to determine the causes of injury.

Table 4. Distribution of Serious Injury and Fatality Crashes

	Incapacitating Injury	**Fatality**	**Percent Fatality**	**% of All Incapacitating Injury and Fatal**
Rollover	46	7	13.2%	46%
Penetration	46	7	13.2%	46%
Both	20	3	13.0%	20%
Neither	44	0	0.0%	38%
Rollover only	26	4	15.4%	25.9%

Impact Angle Distributions

Fig. 23 shows vehicle trajectory angle at impact for crashes involving barrier penetration for both the Missouri and North Carolina data. Note that all of the data shown on this figure are skewed toward higher impact angles. This is especially true for the Missouri data which is limited to serious and fatal injury crashes. The 85th percentile trajectory angles for all penetrations were found to be 39 and 28 degrees for Missouri and North Carolina data respectively. Further, when vehicles rolling over the barrier are eliminated from the MO data, the 85th percentile impact angle for penetration crashes increased to 46 degrees. Note that the NC data includes many minor injury and PDO crashes that are believed to be associated with lower speed penetrations that do not reach opposing traffic lanes. When these cases are removed from the data set its size is reduced below minimum numbers required to establish an accurate distribution.

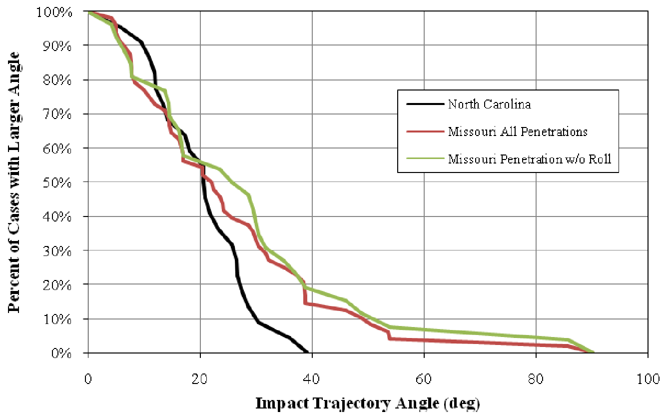

Fig. 23. Distribution of impact trajectory angles observed in North Carolina and Missouri data

Velocity vector angles and vehicle orientation angles at impact were plotted simultaneously to observe trends, and are shown in Fig. 24.

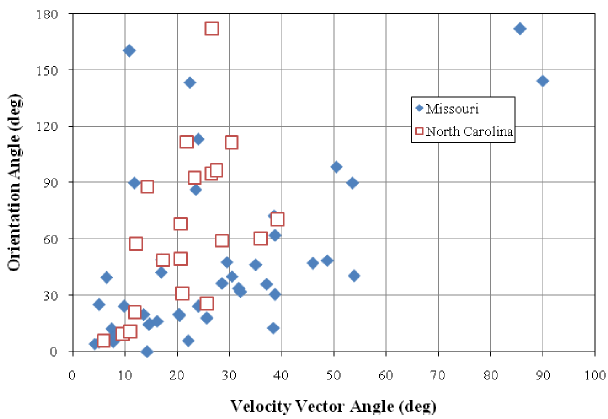

Fig. 24. Velocity vector and orientation angles, penetration impacts

Although there is no clear relationship present, of the 22 penetration crashes in North Carolina and 51 penetration incapacitating injury or fatality crashes in Missouri, only two crashes in each set had orientation angles less than zero degrees. Furthermore, while approximately 30% of the data is had a sideslip angle within 5 degrees, an additional 40% had a sideslip angle more than twice as large as the velocity vector angle.

Upon closer investigation, it was observed that a significant portion of the penetration events could be consolidated into tracking and high-steering zones. The tracking zone was defined by drawing a line with unit slope and encapsulating all of the data points within the tracking margin. Vehicles with sideslip angles less than or equal to 20 degrees were determined to be tracking, based on a variety of control and occupant risk criteria (11). A total of 57% of the penetration crashes in the North Carolina and Missouri databases were tracking at impact. Of the non-tracking impacts, 25% were classified as "high-steering" impacts, based on the vehicle orientation angle at impact with respect to the velocity vector. In these impacts, vehicles steered into the barrier and were involved in pre-crash high yaw-rate maneuvers causing the vehicle to "lead" into the barrier with the front end. The remaining 18% of the crashes had varying impact conditions, not described by either distribution.

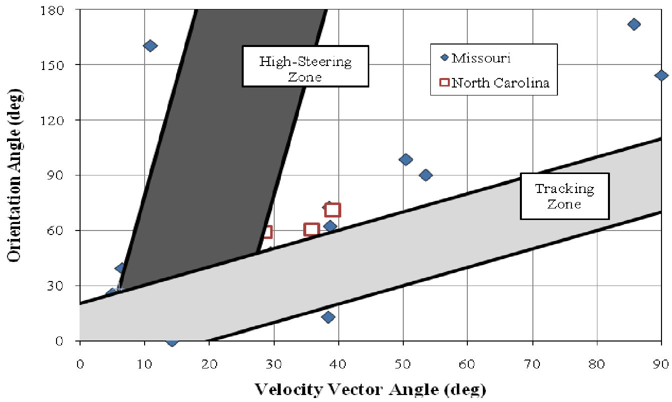

Fig. 25. Zone partition of velocity vector and orientation angles in penetration crashes

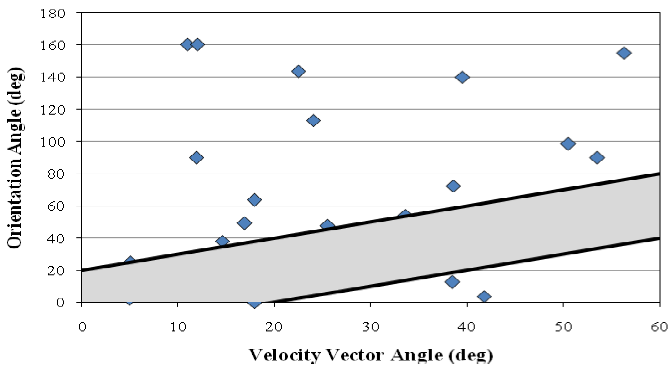

Fig. 26. Velocity vector and orientation angles, rollover crashes

The other high-severity crash type, rollover crashes, was also cross-plotted between orientation and velocity vector angles. Approximately 54% of all incapacitating injury and fatality crashes with cable median barriers resulting in rollover in Missouri occurred with tracking impact conditions. However, of the remaining non-tracking crashes, a pattern of crash conditions could not be identified. Rollover crashes demonstrated a significantly larger variation in crash conditions than the penetration crashes.

Summary and Conclusions

In summary it was found that cable barrier penetrations and rollover crashes typically involve high impact angles and high heading angles with the vehicle contacting the barrier in a more frontal orientation. These findings represent the first objective and statistically significant data that can be used by barrier designers to develop more effective median barrier systems. Further, the accident data indicates that roughly half of the crashes involving barrier failure have impact angles above normal test conditions and many more of these failures are related to high heading angle impacts that are also outside of the normal test or evaluation conditions.

By raising the impact angles for full-scale crash testing to 40°, developers can be assured that their barrier designs are capable of safely accommodating roughly 85% of the crashes currently associated with barrier failure. Further, computer modeling can also be used to evaluate barrier performance during high heading angle impact conditions. The combination of crash testing at higher angles and evaluating high heading angle impacts through computer simulation should allow barrier developers to reduce the frequency of barrier failure, measured in terms of rollovers and penetrations, by at least 50%. As mentioned above, this degree of improvement in barrier performance could save as many as 250 lives per year by the end of this decade.

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