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Secondary Collisions Revisited: Real-World Crash Data and Relationship to Crash Test Criteria

ABSTRACT

Objectives: Previous research conducted in the late 1980's suggested that vehicle impacts following an initial barrier collision increase severe occupant injury risk. Now over 25 years old, the data are no longer representative of the currently installed barriers or the present US vehicle fleet. The purpose of this study is to provide a present-day assessment of secondary collisions and to determine if current full-scale barrier crash testing criteria provide an indication of secondary collision risk for real-world barrier crashes.

Methods: To characterize secondary collisions, 1,363 (596,331 weighted) real-world barrier midsection impacts selected from 13 years (1997-2009) of in-depth crash data available through the National Automotive Sampling System (NASS) / Crashworthiness Data System (CDS) were analyzed. Scene diagram and available scene photographs were used to determine roadside and barrier specific variables unavailable in NASS/CDS. Binary logistic regression models were developed for second event occurrence and resulting driver injury. To investigate current secondary collision crash test criteria, 24 full-scale crash test reports were obtained for common non-proprietary US barriers, and the risk of secondary collisions was determined using recommended evaluation criteria from NCHRP Report 350.

Results: Secondary collisions were found to occur in approximately two thirds of crashes where a barrier is the first object struck. Barrier lateral stiffness, post-impact vehicle trajectory, vehicle type, and pre-impact tracking conditions were found to be statistically significant contributors to secondary event occurrence. The presence of a second event was found to increase the likelihood of a serious driver injury by a factor of 7 compared to cases with no second event present. The NCHRP Report 350 exit angle criterion was found to underestimate the risk of secondary collisions in real-world barrier crashes.

Conclusions: Consistent with previous research, collisions following a barrier impact are not an infrequent event and substantially increase driver injury risk. The results suggest that using exit-angle based crash test criteria alone to assess secondary collision risk is not sufficient to predict second collision occurrence for real-world barrier crashes.

KEYWORDS

Secondary impacts, crash testing, evaluation criteria, longitudinal barriers, injury risk, post-impact vehicle trajectory

INTRODUCTION

Longitudinal barriers are safety features installed adjacent to roadways and include barriers such as w-beam guardrail, cable, or concrete barriers. When a vehicle leaves the roadway, longitudinal barriers are designed to contain and/or redirect the impacting vehicle to prevent it from encountering a more dangerous roadside object or condition. Ideally, the impacting vehicle will be redirected next to the barrier and eventually comes to rest in the roadway shoulder without intruding into any adjacent travel lanes or impacting any other roadside objects.

A secondary impact, also referred to as a secondary collision, is any collision or non-collision event which occurs after an initial barrier impact and redirection. Secondary impacts may include an impact into another barrier, a vehicle-to-vehicle impact, an off-road impact into a fixed object (such as a tree or pole), or a non-collision event such as a rollover. Previous research suggests an increased occupant risk when a secondary collision is present (Ray et al. 1987), but the data used for this research is no longer representative of the current vehicle fleet and current longitudinal barriers installed in the United States. Furthermore, longitudinal barriers are designed and tested in an attempt to minimize the risk of secondary collisions but it is not known whether the criteria used to evaluate full-scale crash tests indicate secondary collision risk in real-world barrier crashes.

BACKGROUND

Prior to field installation, roadside barriers must demonstrate an acceptable level of performance through a series of full-scale crash tests. The Manual for Assessing Safety Hardware (MASH) (AASHTO 2009) outlines full-scale crash testing procedures for longitudinal barriers in the United States. Most of the currently installed longitudinal barriers, however, were tested under requirements listed in National Cooperative Highway Research Program (NCHRP) Report 350 (Ross et al. 1993). Analogous European crash test procedures are outlined in EN-1317 (CEN 1998). These tests evaluate a barrier's performance in three categories: [1] structural adequacy, [2] occupant injury potential, and [3] post-impact vehicle trajectory (AASHTO 2009, Ross et al. 1993, CEN 1998, Bronstad and Michie 1974). The post-impact vehicle trajectory category assesses the behavior of the test vehicle following impact and attempts to provide a general indication of the risk of secondary collisions.

Historically, longitudinal barriers have not been required to pass any specific post-impact vehicle trajectory requirements. Since the establishment of these criteria in NCHRP Report 153 (Bronstad and Michie 1974), the evaluation criteria within the vehicle trajectory category have remained preferred instead of required. Until 2009, the most recent post-impact vehicle trajectory criteria were listed in NCHRP Report 350 and recommended that the vehicle exits the barrier at an angle less than 60 percent of the impact angle and that the vehicle does not intrude into adjacent traffic lanes (Ross et al. 1993).

Two other evaluation criteria for vehicle trajectory were noted, but one criterion is only applicable to end terminal tests and the other criterion was removed with the MASH update because it represents a redundancy with occupant risk criteria. The current MASH vehicle trajectory criteria for longitudinal barriers is a single criterion which recommends the vehicle remains within a restricted 'exit box' for a certain distance after disengaging from the barrier (AASHTO 2009). The exit box dimensions are vehicle dependent and calculated based on the test vehicle length and width. This technique has been used in Europe to evaluate post-impact vehicle trajectory in full-scale crash tests for several years.

Previous Secondary Collision Research

In 1987, Ray et al. investigated the probability of secondary collisions occurring and the injury risk these collisions may present to vehicle occupants. Using 2,405 police reported crashes from New York and North Carolina occurring between 1980 and 1981, the authors investigated injury severity (police reported severe or fatal injuries) and 'rebound' (post-impact vehicle trajectory) characteristics. The cases selected for this study met the following five criteria: [1] a longitudinal barrier was the first object struck, [2] only passenger vehicles were involved, [3] the impact was in the barrier's midsection (i.e. not an end terminal or transition), [4] the impact angle was oblique, and [5] the vehicle was tracking before impact. The authors found that the risk of serious or fatal injury was nearly 3 times greater in crashes in which there was a second event versus those where no second event was present. The authors also found that a second impact with a vehicle in traffic resulted in greater injury severity than a second impact with a fixed object. This research also characterized the post-impact vehicle trajectory of smoothly redirected vehicles and found that in over 75 percent of all cases vehicles were redirected into or across adjacent travel lanes and were at risk of a second collision.

In 1986, Bryden and Fortuniewicz investigated barrier and end terminal accident sites in New York State to determine the effects of various parameters on barrier performance. A total of 3,302 cases where a barrier impact was the first harmful event were analyzed for each case. Information such as vehicle class and type, barrier type, and highway parameters were collected. Secondary collisions were found to occur in about twenty-five percent of all cases, and accounted for nearly 90 percent of the fatal accidents. Almost all of the secondary collisions were either rollovers (33 percent) or impacts into fixed objects (66 percent). Also, passenger cars were found to be involved in second events more often than vans or pickup trucks. Chi-squared analysis showed a statistically significant difference between vehicle weight classes in predicting second event occurrence and containment, with heavier vehicles exhibiting higher second collision rates and more dangerous post-impact trajectory than lighter vehicles.

More recently, Gabauer (2010) investigated 12 years (1997-2008) of real-world crash data to determine the frequency of secondary impacts, the resulting influence they have on occupant injury, and how factors such as barrier type and vehicle type affect the occurrence and severity of these crashes. The cases selected for the study met the following criteria: [1] a longitudinal barrier was the first object struck (midsections or end terminals) and [2] only passenger vehicles were involved. Using the

NASS/CDS database and weighting factors, a total of 2,026 cases (1,004,678 weighted) were selected for analysis. Secondary impacts were found to occur in approximately 34 percent of all cases. This study found that vehicles crossed into travel lanes after an initial impact in approximately 58 percent of all cases and were redirected next to the barrier in about 33 percent of all cases. It was determined that SUVs represent the most at-risk vehicle type and over 50 percent of cases involving SUVs were involved in a secondary impact.

OBJECTIVES

The purpose of this study was to investigate secondary collisions following an impact with a longitudinal barrier from both a real-world crash and full-scale crash testing perspective. The specific objectives were: [1] to determine the characteristics of real-world secondary collisions and their effect on driver injury and [2] to assess how well post-impact vehicle trajectory criteria used in full-scale crash testing provide an indication for the risk of secondary collisions in real-world barrier crashes.

METHODS

Secondary collisions were investigated by two different means: [1] an analysis of real-world crash cases with descriptive statistics and statistical modeling and [2] an analysis of full-scale crash tests and the evaluation criteria related to post-impact vehicle trajectory. The analyses of real-world cases and full-scale crash tests were compared to assess how well the risk of secondary collisions is indicated by barrier crash test evaluation criteria. These two parts of the study required differing methodologies, each discussed in more detail in the subsequent sections.

Real-World Barrier Crash Analysis

Case selection: Data was selected from 13 years (1997-2009) of in-depth crash data available through the National Automotive Sampling System (NASS) / Crashworthiness Data System (CDS). Maintained by the NHTSA, NASS/CDS is a nationally representative annual sample of approximately 5,000 U.S. crash cases that contains very detailed vehicle and occupant injury information (NCSA 2009). Case selection is based on a complex sampling scheme which assigns a weighting factor to each case; the application of the weighting factors to the cases provides a nationally representative estimate. For this study, cases from the NASS/CDS database were selected based on the following three criteria:

[1] <u>A longitudinal barrier was the first object struck</u>. Both single and multi-vehicle impacts were included, as long as a barrier was the first object contacted by the vehicle. This ensured the cases were comparable to full-scale longitudinal barrier crash tests. Cases where a vehicle impacted a barrier not specifically designed to redirect a vehicle were excluded. Such barriers included, but were not limited to, fences, high curbs, or planter boxes.

[2] Only passenger vehicles were included. NASS/CDS focuses on passenger vehicle crashes and excludes large truck and motorcycle crashes (NCSA 2009). Vehicles towing a trailer were also excluded from the present study because passenger vehicles towing trailers have not been evaluated with full-scale crash testing and may cause unexpected vehicle response during redirection.

[3] The vehicle impacted the barrier midsection. To measure the performance of a typical barrier section, only barrier midsection impacts were included. Unlike the Gabauer (2010) study, end terminals were excluded so that comparisons to analogous crash tests may be made for specific barrier types. Also, end terminals are designed to perform differently than midsection longitudinal barriers and, likewise, have different performance requirements for vehicle trajectory. The portion of roadside barriers that will be referred to as the barrier midsection or length of need is referred to as the 'standard section' in the 2011 Roadside Design Guide (AASHTO 2011). Transition sections, which are sections designed to join barriers with differing lateral stiffness, were also excluded. Transitions typically have varying post spacing and are designed to perform differently than typical barrier midsections. Further, initial investigation of available data indicated only a small number of transition crash cases available for analysis.

These selection criteria have been chosen to generate a data set which may be accurately compared to full-scale crash tests of longitudinal barriers. The selection criteria above are similar to the criteria used by Ray et al. (1987) except that there is no limitation of vehicle impact angles or pre-impact tracking conditions for this study. These criteria were excluded because full-scale crash tests are intended to represent practical worst-case impact conditions for real world barrier impacts and research conducted by Stolle et al. (2011) suggests that non-tracking conditions often precede real-world barrier impacts.

Database development with additional roadside data elements: While the NASS/CDS database contains vehicle and occupant related variables for each investigated case, there are very few details provided for the roadside or any involved barriers. Gabauer (2010) determined barrier and redirection information for end terminal and midsection barrier impacts from 1997-2008 and added this data to the available NASS/CDS information to develop an improved data set. Using this improved database, some of the data elements were used to filter and select appropriate cases for this study according to the previously outlined selection criteria. Two phases of database development were then performed to first quality control and re-assess variables added by Gabauer (2010) and then to add more detailed and specific information related to the impact conditions and resulting vehicle behavior for each case. All data elements developed and added to the NASS/CDS cases during these phases are listed and briefly described in Table 1.

For the initial phase of data development, data for impacts occurring in 2009 were added to Gabauer's existing data and the entire sample of cases was reviewed three separate times to ensure consistency within the newly added variables. Similar coding techniques were used as presented by Gabauer (2010) and may be generally comparable to those used by Ray et al. (1987). In some instances, NASS/CDS investigators have labeled single-barrier impacts as multiple event occurrences due to multiple parts of the vehicle impacting the barrier during a single redirection event (i.e. event 1 is the vehicle front corner impacting the guardrail and event 2 is the vehicle side impacting the guardrail). For the purposes of this study, such cases have been re-labeled to indicate a single barrier impact. Barrier penetration was considered present if the vehicle went over, under, on top of, or through the barrier. The presence of barrier penetration does not necessarily indicate that the vehicle went completely through the barrier; in some cases vehicles rode on top of a barrier before hitting an object on top or returning to the roadway. When classifying the post-impact vehicle trajectory for each case, five scenarios were possible. A description of each scenario and the corresponding designation is summarized in Table 1.

To begin the second phase of data development, the post-impact vehicle trajectory for each case was re-evaluated by modifying the criteria for determining whether a case was 'next to barrier' or 'into adjacent lanes.' For the Gabauer (2010) study, cases were labeled 'next to barrier' if the vehicle intruded into the first travel lane when no shoulder was present. For this study, post-impact vehicle trajectory could only be classified as 'next to barrier' if it did not intrude into the roadway during and after redirection. The barrier offset at the point of impact was estimated for each case. This was achieved by reviewing at least 5 scene photographs of the impact area and determining whether a full shoulder was present at the point of impact. The number of scene photographs varied with each case, but only cases with several clear photographs of the impact area were included. Barrier offset would ideally be measured quantitatively, but due to a lack of information and varying levels of photographic documentation of the roadside for each case, an approximate shoulder width classification was used as an indicator of barrier offset. If it appeared that a typical large passenger vehicle could fit safely between the barrier and first lane, barrier offset was labeled as 'FULL,' otherwise it was labeled as 'NONE.'

TABLE 1 Roadside, Barrier, and Redirection Variables Used to Supplement the NASS/CDS Database

Variable	Values	Description
Barrier Class	CONCRETE	Concrete barrier
	METAL	Metal barrier
Barrier Lateral Stiffness	FLEX	Cable and weak post W-beam barriers
	SEMI	Box beam, strong post W-beam, and thrie beam barriers
	RIGD	Concrete barrier types
Barrier Type	NJ	Safety Shape barrier (including New Jersey and F-Shape)
	SS	Single Slope barrier
	VW	Vertical Wall barrier
	CABLE	Cable barrier
	SPWB	Strong Post W-Beam barrier
	WPWB	Weak Post W-Beam barrier
	SPTB	Strong Post Thrie Beam barrier
	BB	Box Beam barrier
Impact Location	LON	Impact into a Length of Need/Midsection
	ET	Impact into an End Terminal
Second Event	YES	A Second Event was present
	NO	No Second Event was present
Barriers Involved	ONE	One barrier was impacted
	SAME	The same barrier was impacted twice or more
	DIFF	Two different barriers were impacted
Barrier Penetration	YES	Barrier penetration was present
	NO	Barrier penetration was not present
Post-Impact Vehicle Trajectory	BB	Any part of the vehicle goes through or over the barrier. This designation includes all cases in which penetration occurs.
	BY	The vehicle travels beyond the length of the barrier without intruding into any travel lanes.
	NB	The vehicle comes to rest next to the barrier without intruding into any adjacent travel lanes.
	LL	The vehicle intrudes into one or more travel lanes without crossing all possible travel lanes.
	AL	The vehicle crosses all same-direction travel lanes
Final Resting Position	BB	The vehicle comes to rest behind the barrier after experiencing some form of barrier penetration
	BY	The vehicle comes to rest beyond the length of the barrier without intruding into any travel lanes
	NB	The vehicle comes to rest next to the barrier with no parts of the vehicle intruding into any adjacent travel lanes
	LL	The vehicle comes to rest intruding into one or more travel lanes without crossing into all possible lanes
	AL	The vehicle comes to rest across all lanes or intruding into the furthest travel lane from the initial impact
Number of Lanes	1,2,3,4,…	The number of active travel lanes (including on/off ramps) at the impact location was recorded
Barrier Lateral Offset	FULL	The barrier lateral offset is wide enough to safely fit a large passenger vehicle
	NONE	The barrier lateral offset is not as wide as a large passenger vehicle

The designations used for post-impact vehicle trajectory were also used to classify the location of final rest for each vehicle. By using the same designations for post-impact vehicle trajectory and final rest, a better understanding of the redirection event was possible. This new scheme allows for the post-impact vehicle trajectory to represent the maximum level of roadway intrusion after the initial impact but before a second event and the final resting position to provide some idea of vehicle trajectory after the second event (in both cases, only if there is a second event present). Therefore, if there was no second event present, then the classification for post-impact vehicle trajectory and location of final rest were coded the same.

Statistical models: To determine the most significant factors contributing to the occurrence of second events and their resulting injury severity, Statistical Analysis Software (SAS version 9.2) was used to analyze weighted frequencies and create statistical models based on the available NASS/CDS variables, barrier and roadside supplemental variables, and other derived variables. To find the 95 percent confidence intervals for frequency data, the SAS "SURVEYFREQ" procedure was used, which estimates variance using Taylor Series Linearization. Both binary logistic regression models were developed using the SAS "SURVEYLOGISTIC" procedure which takes into account the complex sample design of NASS/CDS.

A binary logistic regression model was developed to predict the presence of a second event following an initial barrier impact. The explanatory variables for this model were pre-impact tracking conditions, barrier lateral stiffness, vehicle type, and post-impact vehicle trajectory. The tracking variable is a dichotomous variable indicating whether the vehicle was tracking or non-tracking prior to impact. An initial investigation of the barrier type variable for the available data revealed that some barrier types had an insufficient number of raw cases to produce a meaningful analysis. Available barrier types were classified into flexible (cable and weak post w-beam), semi-rigid (box beam, strong post w-beam, and thrie beam), and rigid systems (all concrete barriers) to better represent barriers of differing lateral stiffness. An initial analysis of post-impact vehicle trajectory revealed that this effect was significant, but it was also found that less than 1 percent of all cases were redirected beyond 2 lanes without crossing all available lanes. Therefore, post-impact vehicle trajectory was re-coded to represent intrusion into a theoretical 2 lane roadway.

A binary logistic regression model was also used to predict the likelihood of a driver suffering a severe or fatal injury. For the injury severity model, only driver injuries were investigated and cases involving partially-or-fully ejected drivers were excluded since the ejection was most likely the cause of any severe injuries. Driver injury for each case was reported as an Abbreviated Injury Severity (AIS) (AAAM 2008) score; a threat-to-life based injury rating ranging from 0 (no injury) to 6 (fatal injury). For the purposes of this study, the most severe AIS score for each driver (referred to as the maximum AIS or MAIS) was transformed into a dichotomous variable with either a mild (no injury, minor or moderate injury; MAIS 0-2) or severe (serious, severe, critical, or fatal injury; MAIS 3-6) outcome. Cases with unknown injury severity were omitted. The explanatory variables for the injury severity model were second event presence, barrier lateral stiffness, vehicle type, restraint use, and barrier penetration. Second event presence, restraint use, and barrier penetration are dichotomous response variables, while barrier lateral stiffness and vehicle type have three categories as described previously. For restraint use, the driver was considered to have used a restraint if either a manual or passive seat belt was used with both a lap belt and shoulder belt. The driver was considered unrestrained if no belt was used or if either belt (lap or shoulder) was used without the other. Cases with unknown restraint usage were omitted.

Full-Scale Crash Test Analysis

Case selection: Reports for full-scale barrier crash tests were obtained from several sources including Texas Transportation Institute (TTI), the Midwest Roadside Safety Facility (MwRSF), and the California Department of Transportation. In an effort to assess the post-impact performance of commonly installed longitudinal barriers, only non-proprietary barrier systems were selected for analysis. A recent survey of State officials by Bullard et al. (2010) found that the 20 most common barrier types in the United States were non-proprietary systems. To include only crash tests comparable to the real-world cases previously selected, only tests involving standard 820C, 1100C, 2000P, and 2270P vehicle designations were selected. Each vehicle designation indicates the vehicle weight in kilograms (i.e. 820kg, 1100kg) followed by a letter designation to differentiate cars (C) from pickup trucks (P). Although the testing procedures do not specify or require any particular vehicle make or model, common test vehicles used in longitudinal barrier testing include the Geo Metro (820C), the Kia Rio (1100C), the Chevrolet C2500 Regular Cab Pickup (2000P), and the Dodge Ram 1500 Quad Cab Pickup (2270P). The available test reports also had to have sufficient redirection information and a scaled trajectory diagram from which to gauge roadway intrusion. Although there were some MASH-based full-scale crash tests available using the recommended exit box criterion, there were not enough tests to draw any meaningful conclusions about the exit box’s ability to account for secondary impact risk.

Vehicle trajectory criteria and analysis methodology: There are some known issues with using crash test trajectory as a measure of secondary event risk, and MASH notes that, "...because driver response in avoiding secondary collisions is not simulated in the crash tests, it seems inappropriate to predict in-service performance based on the complete test trajectory (AASHTO 2009)." Despite this, full-scale crash testing is meant to account for some level of real-world performance. In regards to vehicle trajectory, MASH later indicates, “User agencies should assess the post-impact vehicle trajectory of a roadside safety feature in light of the actual field conditions. For many tests, a scaled diagram showing the post-impact trajectory of the vehicle, including the point of final rest, should provide sufficient information for the user agencies to make their assessment (AASHTO 2009).” Following MASH guidance, vehicle roadway intrusion during redirection was estimated for each crash test case and vehicle using scaled diagrams, labeled roadway intrusion values (when available), and/or scaled vehicle dimensions.

For each crash test case, the recommended exit angle criterion from NCHRP Report 350 was determined. Every crash case had an impact and exit angle listed, so it was determined whether the exit angle was less than 60 percent of the impact angle for each case. Next, using the five possible classifications discussed earlier for real-world crash cases, the post-impact vehicle trajectory for each full-scale crash test was determined by superimposing a theoretical two-lane roadway with a full shoulder over each test area. For each report, the scaled diagram of the test vehicle trajectory was used in conjunction with the labeled lateral offset at final rest to estimate a quantitative level of intrusion into a hypothetical two-lane roadway. Most reports did not include the approximate wheel track during redirection and for such cases the vehicle position at final rest was used as a measure of roadway intrusion. To quantify levels of intrusion into the hypothetical roadway, the 2011 AASHTO Green Book (AASHTO 2011) was used to prescribe a minimum width of 10 feet (3 meters) for the outside shoulder and 12 feet (3.33 meters) for each lane. Roadway intrusion of less than 10 feet laterally from the barrier was considered safe redirection and roadway intrusion over 10 feet laterally into the roadway was considered a risk of a second event.

After determining roadway intrusion according to the NCHRP Report 350 exit angle criterion and MASH guidance, a composite risk of secondary collision was determined. If a case failed one or both of these evaluation criteria it was determined to have shown a risk of a second event. After determining the risk of secondary impacts for metal and concrete barriers as shown in full-scale crash testing, the proportion of cases exhibiting a risk of secondary impacts was compared to real-world data along with the post-impact vehicle trajectory characteristics of both data sets.

RESULTS

Real World Barrier Crash Analysis

Descriptive statistics: A total of 1,363 real world barrier crash cases met the three selection criteria and were included in the analysis. Using NASS/CDS weighting factors, these cases represent nearly 600,000 vehicle-to-barrier impacts. It was found that second events occurred in approximately two-thirds of the available cases (66% weighted; 95% CI = 57.5-74.8). There are slightly more concrete barrier cases than metal barrier cases, with approximately 55% (95% CI = 45.9-63.8) of the weighted cases involving concrete barriers and approximately 45 percent (95% CI = 36.1-54.1) involving metal barriers. Other characteristics of the data including the presence of barrier penetration, post-impact vehicle trajectory, barrier type, and vehicle type are shown in Table 2.

For both barrier classes, a single barrier type represented most of the cases. Strong post w-beam barriers represented 75 percent (95% CI = 64.5 – 86.0) of the metal barriers, and safety shape barriers (including New Jersey, F-shape, and Ontario barrier types) represented 96 percent (95% CI = 94.4 – 99.7) of concrete barrier cases. The barrier type labeled ‘unknown concrete’ was included because some barriers could clearly be identified as a standard concrete barrier type, but due to poor photo documentation or poor atmospheric conditions at the time of documentation, their exact type could not be discerned. These cases were saved for analysis of the concrete barrier class, but are not included in any barrier type analysis. Approximately 64 percent (95% CI = 53.7 – 75.1) of metal barrier cases and 68 percent (95% CI = 55.6 – 81.1) of concrete barrier cases were found to have second events. When second events did occur, concrete or metal barriers were the most commonly struck objects. As shown in Table 2, other second events included impacts into other vehicles, rollovers, and impacts into poles or trees.

TABLE 2 Characterization of the Real World Barrier Crash Data Set [NASS/CDS 1997-2009, inclusive]

Variable	Raw Cases	Weighted	Weighted Percent
All	1,363	596,331	-
Second Event			
Yes	1,137	394,417	66.1
No	226	201,914	33.9
Penetration			
Yes	113	17,495	2.9
No	1250	578,836	97.1
Vehicle Trajectory			
Next To Barrier (NB)	124	107,533	18.1
Into Adjacent Lanes (LL)	455	185,187	31.2
Across All Lanes (AL)	642	252,844	42.6
Beyond Barrier (BY)	34	31,098	5.2
Behind Barrier (BB)	106	17,157	2.9
Barrier Type			
Concrete	*761*	*326,560*	*54.9*
Safety Shape	700	307,192	94.1
Single Slope	22	6,966	2.1
Vertical Wall	9	4,080	1.3
Unknown Concrete	30	8,321	2.5
Metal	*601*	*268,997*	*45.1*
Strong Post W-Beam	462	202,416	75.2
Weak Post W-Beam	38	17,936	6.7
Thrie Beam	65	22,663	8.4
Box Beam	21	16,356	6.1
Cable	15	9,625	3.6
Vehicle Type			
Car	934	421,495	70.7
Pickup Truck	152	76,707	12.9
SUV	277	98,130	16.4
Object Struck (Second Event)			
Concrete Barrier	437	151,827	38.5
Metal Barrier	327	113,369	28.8
Other Vehicle	139	47,989	12.2
Rollover	58	20,062	5.1
Pole/Tree	49	16,962	4.3
Embankment	33	11,410	2.9
Other Fixed Object	20	6,976	1.8
Other	73	25,308	6.4
Number of Lanes			
One Lane	62	19,465	3.3
Two Lanes	474	255,422	42.8
Three Lanes	408	136,508	22.9

Statistical model results: Two binary logistic models were developed to predict the likelihood of a secondary event and to predict the likelihood of suffering a severe injury. The significance of various explanatory variables was investigated as part of the model development process. Variables found to have no statistically significant effect on the occurrence or severity of a secondary event were vehicle model year, vehicle weight, atmospheric conditions (rain, snow, etc.), roadway alignment, functional class, and lighting conditions. The results of the second event presence model are summarized in Table 3.

TABLE 3 Statistical Indicators for Second Event Presence Model

Statistical Indicators			
Parameter	**Wald χ^2**	**P**	**C**
Barrier Lateral Stiffness	7.17	0.0277	0.73
Vehicle Type	22.46	< 0.0001	
Post-Impact Vehicle Trajectory	58.09	<0.0001	
Tracking	9.17	0.0025	

Odds Ratio Estimates				
Parameter	**Value**	**Comparison**	**Odds Ratio**	**95% CI**
Barrier Lateral Stiffness	Flexible	Semi-Rigid	8.06	1.7 - 37.4
	Rigid	Semi-Rigid	1.64	0.8 - 3.2
Vehicle Type	SUV	Car	8.17	3.4 - 19.5
	Truck	Car	1.65	0.6 - 4.8
Post-Impact Vehicle Trajectory	Across All Lanes	Next to Barrier	52.84	17.9 - 156.4
	Into Adjacent Lanes	Next to Barrier	15.34	6.6 - 35.4
	Beyond Barrier	Next to Barrier	3.13	0.4 - 25.3
	Behind Barrier	Next to Barrier	9.66	2.0 - 45.9
Tracking	Tracking	Non-Tracking	3.07	1.5 - 6.4

The high C-statistic indicates good model fit, and the *p*-values for the explanatory variables indicate that the effects of these variables are all statistically significant to the 95 percent confidence level. For each odds ratio estimate, the parameter values listed are in comparison to the value listed in the ‘comparison’ column. All post-impact vehicle trajectories are significantly more likely to result in a second event than redirection ‘next to barrier,’ and vehicle tracking prior to impact were found to be approximately 3 times more likely to result in a second event compared to non-tracking cases.

A second model was developed to predict severe driver injury in vehicle to barrier impacts. A summary of statistical parameters for the model are shown in Table 4.

TABLE 4Statistical Indicators for Driver Injury Severity Model

Statistical Indicators			
Parameter	**Wald χ^2**	**P**	**C**
Second Event	5.61	0.0178	0.65
Barrier Lateral Stiffness	0.94	0.6238	
Vehicle Type	11.74	0.0028	
Restraint Use	2.96	0.0851	

Odds Ratio Estimates				
Parameter	**Value**	**Comparison**	**Odds Ratio**	**95% CI**
Second Event	Yes	No	6.98	1.4 - 34.8
Barrier Lateral Stiffness	Semi-Rigid	Flexible	1.85	0.3 – 10.1
	Rigid	Flexible	1.13	0.3 – 5.0
Vehicle Type	Car	Pickup Truck	9.05	2.5 – 32.7
	SUV	Pickup Truck	2.55	0.6 – 11.3
Restraint Use	None	Lap & Shoulder	2.27	0.9 – 5.7

The C-statistic indicates good model fit, and the parameter *p*-values indicate that barrier lateral stiffness and restraint use are the only variables which are not statistically significant. The presence of a second event was found to increase the likelihood of experiencing a severe or fatal injury by a factor of 7 when compared to a crash with no second event. Cars were found to be the only statistically significant vehicle type, and car drivers were estimated to be 9 times more likely to experience a severe or fatal injury than drivers of pickup trucks. Drivers not using restraints were found to be about two times more likely to experience a severe or fatal injury than belted drivers.

Full-Scale Crash Testing

Crash test reports were obtained for w-beam barriers, safety shape barriers, and cable barriers. Despite a large number of available cable barrier test reports, there were only fifteen real-world cable barrier cases, so this barrier type was excluded for full-scale crash test analysis. After excluding proprietary barriers, a total of 16 w-beam reports and 8 concrete safety shape reports were selected for analysis. For each report, relevant information such as the barrier details, vehicle details, impact/exit conditions, and test number were recorded. To help determine an approximate roadway intrusion value for each case based on the scaled trajectory diagrams, the length and width of each test vehicle was found using information available in NHTSA's Vehicle Crash Test Database. A summary of the available w-beam and safety shape barrier systems, along with their test report information and testing agency are listed in Table 5.

Quantitative values for roadway intrusion during a vehicle's post-impact trajectory are not readily available or reported, so the recommended NCHRP Report 350 (Ross et al. 1993) guideline of having an exit angle less than 60 percent of the impact angle was first used to evaluate w-beam and safety shape crash test cases. When using this single criterion, w-beam barriers exhibited unsafe post-impact vehicle trajectory in just over 30 percent of cases, and safety shape barriers exhibited unsafe post-impact vehicle trajectory less than half as much, approximately 13 percent of safety shape barrier crash tests (Figure 1).

Next, the risk of a second event was estimated by using scaled trajectory diagrams to evaluate each test vehicle's intrusion into a theoretical 2 lane roadway as previously discussed. If a case was found to fail the exit angle or roadway intrusion evaluation criteria, the test vehicle was considered at risk of experiencing a secondary event. Using this improved process loosely recommended by guidance noted in MASH, the risk of a second event was found to be present in about 87 percent of w-beam cases and 75 percent of safety shape cases. Overall, this evaluation technique overestimated secondary impact risk, but these higher percentages were an improvement over the exit angle criterion which drastically underestimated secondary impact risk. A comparison of secondary event risk in full-scale crash test data and second event presence in real world crash data are shown in Figure 1.

FIGURE 1 Second event presence in real world data and second event risk in crash test data

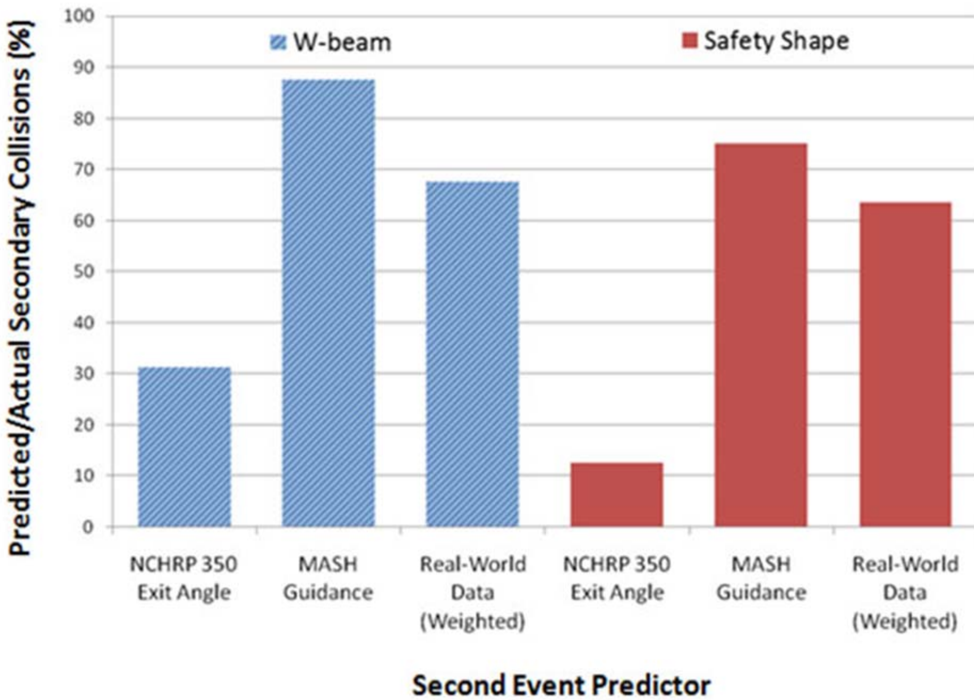

TABLE 5 Full-Scale Barrier Crash Test Report Information and Testing Agencies

Barrier Type	System Name	Acceptance Letter or Test Number	Testing Agency	Year
Strong Post W-Beam	Midwest Guardrail System	b-133	Midwest Roadside Safety Facility	2001
	Midwest Guardrail System	b-133	Midwest Roadside Safety Facility	2002
	Midwest Guardrail System	b-133	Midwest Roadside Safety Facility	2002
	Midwest Guardrail System	b-133	Midwest Roadside Safety Facility	2002
	Midwest Guardrail System	b-175	Midwest Roadside Safety Facility	2006
	Midwest Guardrail System	b-175	Midwest Roadside Safety Facility	2006
	G4 Guardrail	b-80	Texas Transportation Institute	2000
	Modified G4 (1S) Guardrail	b-156	South West Research Institute	2006
	Modified G4 (1S) Guardrail	2214WB-1	Midwest Roadside Safety Facility	2004
	Modified G4 (1S) Guardrail	2214WB-2	Midwest Roadside Safety Facility	2005
	Midwest Guardrail System	2214MG-1	Midwest Roadside Safety Facility	2004
	Midwest Guardrail System	2214MG-2	Midwest Roadside Safety Facility	2004
	Midwest Guardrail System	2214MG-3	Midwest Roadside Safety Facility	2004
	G4 (1S) Guardrail	RF-476460-1-10	Texas Transportation Institute	2009
	G4 (2W) Guardrail	RF-476460-1-5	Texas Transportation Institute	2009
	G2 Guardrail	RF-476460-1-7	Texas Transportation Institute	2009
Concrete Safety Shape	Type 70 Concrete Bridge Barrier	b-45	California DOT	1997
	Type 60G Concrete Barrier	b-45	California DOT	1995
	F-Shape Barrier	452106-3	Texas Transportation Institute	2006
	Idaho DOT Concrete Barrier (NJ)	13-4300-001	E-TECH Testing Services	2000
	Idaho DOT Concrete Barrier (NJ)	13-4300-002	E-TECH Testing Services	2000
	NJ Safety Shape	476460-1-4	Texas Transportation Institute	2009
	NJ Safety Shape	551	California DOT	1999
	NJ Safety Shape	552	California DOT	1999

DISCUSSION

The available real-world crash data indicates that secondary events occur in approximately two-thirds of all vehicle-to-barrier collisions. In approximately 74 percent of all vehicle-to-barrier crashes, the vehicle was redirected into or across all lanes and was at risk of a second collision. This finding is very similar to the Ray et al. study (1987) which found that just over 75 percent of all smoothly redirected vehicles experienced similar roadway intrusion. Despite using a similar analysis technique including the application of NASS/CDS weights, the most recent secondary impact research by Gabauer (2010) found redirection into travel lanes in 58 percent of all cases which is slightly lower than the value in the current study. At least part of this discrepancy may be attributed to the fact that the Gabauer data included both end terminal impacts and barrier midsection impacts. Depending on the exact impact point, end terminals can function very differently than the barrier midsection and vehicles impacting them are likely to have differing secondary collision characteristics. In addition, the reevaluation of the post-impact vehicle trajectory likely resulted in a larger percentage of vehicles encroaching into adjacent lanes as the original Gabauer study generally coded 'next to barrier' irrespective of roadway shoulder presence. Sport utility vehicles (SUVs) were found to be over 8 times more likely to experience a second event than passenger cars. This supports a previous finding by Gabauer (2010) that also found SUV to be the most at-risk vehicle type. Post-impact vehicle trajectory ‘beyond barrier’ only occurred in 34 raw cases and was not found to be statistically significant.

Secondary event rates were found to be approximately equal for rigid and semi-rigid barriers, suggesting that neither barrier type exhibits notably safer vehicle redirection than the other. The similarity in secondary collision rates between rigid and semi-rigid barrier systems may be due to the fact that they are designed to limit barrier deflection (to a similar degree) much more than flexible barriers. Flexible barrier systems were found to be approximately 8 times more likely than semi-rigid systems to result in a secondary event but only 53 raw cases were available for analysis. This small number of cases may have caused some variance in the data, as indicated by the large confidence interval. Variables found to have no significant effect on the occurrence of secondary events included roadway functional class, roadway alignment, roadway surface type/condition, speed limit, shoulder presence, lighting conditions and the number of travel lanes. Unlike the findings of Bryden and Fortuniewicz (1986), vehicle weight was found to have no significant effect in either model.

The presence of a second event was found to increase the likelihood of the driver experiencing a severe or fatal injury by a factor of 7 when compared to a crash with no second event. This factor is approximately twice as large as previous findings by Ray et al. (1987) and Gabauer (2010) which both estimated the presence of a second event to increase the likelihood of a severe injury by a factor of approximately 3-3.5. The 95 percent confidence bounds for the second event presence effect are rather wide (1.4 - 34.8), but estimates from both the Ray et al. (1987) and Gabauer (2010) studies are contained within this interval. This large uncertainty suggests that the relatively small number of raw cases may have reduced the sensitivity of the model to detect differences in the data set, especially when controlling for other factors. Before the application of NASS/CDS weights, the presence of a second event was found to increase the likelihood of experiencing a severe or fatal injury by a factor of approximately 3.3 when compared to a crash with no second event (Severe/fatal driver injuries were present in 8 percent of cases with no second event and 26 percent of cases in which a second event was present). Restraint use was not found to be statistically significant (to the 95 percent level), but the p-value ($p = 0.0851$) suggests that this variable was near the threshold and may be of interest. The odds ratio comparison for restraint use indicates that the lower bound of the 95 percent confidence interval is nearly 1 and suggests that unbelted drivers are 2.2 times more likely to suffer severe or fatal injury than belted drivers.

There were a relatively small number of full-scale crash test cases available for analysis, but it should be noted that the number of desired cases available was small due to the limited frequency of such tests, especially multiple tests of the same barrier and vehicle type. The limited number of tests can be attributed to many factors, including the fact that full-scale crash tests are expensive and for most barriers only a few tests with different vehicle types are ever performed. Analyzing a small sample is not ideal, but a loose comparison of the results for real world crashes and crash testing as shown in Figure 1 can serve as a starting point for future investigations. The data in Figure 1 indicates that using exit angle alone as an evaluation criterion for real-world post-impact vehicle trajectory may not be suitable and appears to underestimate the risk of secondary collisions as evident in full-scale longitudinal barrier crash tests. Figure 1 also shows that the MASH guided exit box and exit angle used together as criteria may provide a more reliable evaluation of post-impact vehicle trajectory. Despite the improvement shown using both criteria, the effectiveness of using solely the exit box to evaluate post-impact vehicle trajectory could not be determined due to a lack of available MASH crash tests. In the future, it would be useful to have the exit box extents clearly shown in each crash test report's vehicle path diagram. It would also be useful if each test installation included lines painted parallel to the barrier to indicate the approximate location of a full shoulder and 2 travel lanes. Regardless of whether modifications are made to crash testing procedures, more full-scale crash tests are necessary before the effectiveness of the exit box criteria can be evaluated.

CONCLUSION

This study has investigated secondary events following longitudinal barrier impacts in tow-away level crashes. Some main findings were:

Real-World Barrier Impacts

- Secondary events were found to occur in approximately two-thirds of all cases in which a roadside barrier was the first object impacted.
- Barrier lateral stiffness, vehicle type, post-impact vehicle trajectory, and pre-impact tracking were found to be statistically significant contributors to the likelihood of a second event. SUV's were found to be 8 times more likely than cars to experience a second event while a vehicle redirected across all lanes was found to be approximately 53 times more likely to be involved in a second

event than if the vehicle was redirected next to the barrier. Vehicle tracking prior to impact was found to increase the likelihood of a secondary event by a factor of 3.

- The presence of a second event, vehicle type, and barrier penetration were found to be statistically significant contributors to the likelihood of a severe or fatal injury. The presence of a second event was found to increase the likelihood of a severe or fatal driver injury by a factor of 7. Unbelted drivers were also found to be 2.2 times more likely than unbelted drivers to suffer a severe or fatal injury. Passenger cars were found to be approximately 9 times more likely than pickup trucks to allow a severe or fatal injury.

Crash Test Criteria

- The NCHRP Report 350 (Ross et al. 1993) exit angle criterion alone was not sufficient to predict second collision occurrence for real-world barrier crashes.
- Using NCHRP Report 350 (Ross et al. 1993) vehicle trajectory criteria and recommended MASH (AASHTO 2009) guidelines together, w-beam and safety shape barrier crash tests were found to overestimate second event occurrence.

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