2012

Real-World Performance of Longitudinal Barriers Struck by Large Trucks

Doug Gabauer
Bucknell University, dg027@bucknell.edu

Recommended Citation
Gabauer, Doug. "Real-World Performance of Longitudinal Barriers Struck by Large Trucks." *Transportation Research Record: Journal of the Transportation Research Board* (2012) : 127-134.

REAL-WORLD PERFORMANCE OF LONGITUDINAL BARRIERS STRUCK BY LARGE TRUCKS

Douglas J. Gabauer

Assistant Professor
Department of Civil and Environmental Engineering
Bucknell University
Lewisburg, PA 17837
Phone: (570) 577 – 2902
Fax: (570) 577 – 3415
E-Mail: doug.gabauer@bucknell.edu

TRB Paper: 12-4358

Word Count: 5,539 (text-only) + 1,750 (6 Tables, 1 Figure) = 7,289 (including figures and tables)

Abstract

Outside of relatively limited crash testing with large trucks, very little is known regarding the performance of traffic barriers subjected to real-world large truck impacts. The purpose of this study was to investigate real-world large truck impacts into traffic barriers to determine barrier crash involvement rates, the impact performance of barriers not specifically designed to redirect large trucks, and the real-world performance of large-truck-specific barriers. Data sources included the Fatality Analysis Reporting System (2000-2009), the General Estimates System (2000-2009) and 155 in-depth large truck-to-barrier crashes from the Large Truck Crash Causation Study. Large truck impacts with a longitudinal barrier were found to comprise 3 percent of all police-reported longitudinal barrier impacts and roughly the same proportion of barrier fatalities. Based on a logistic regression model predicting barrier penetration, large truck barrier penetration risk was found to increase by a factor of 6 for impacts with barriers designed primarily for passenger vehicles. Although large-truck-specific barriers were found to perform better than non-heavy vehicle specific barriers, the penetration rate of these barriers were found to be 17 percent. This penetration rate is especially a concern because the higher test level barriers are designed to protect other road users, not the occupants of the large truck. Surprisingly, barriers not specifically designed for large truck impacts were found to prevent large truck penetration approximately half of the time. This suggests that adding costlier higher test level barriers may not always be warranted, especially on roadways with lower truck volumes.

INTRODUCTION

Longitudinal barriers such as w-beam guardrails are designed and installed to prevent vehicles from impacting a more dangerous hazard such as a fixed object, a steep slope, or a vehicle in an opposing lane of traffic. The vast majority of the barriers that line US highways were designed and crash tested to redirect only passenger vehicles, namely a small car and large pickup truck. There have been several longitudinal traffic barriers and bridge rails, primarily concrete barriers, that have been developed and crash tested to resist impacts from large trucks (> 4,536 kg gross vehicle weight rating). Outside of relatively limited crash testing with large trucks, however, very little is known regarding the performance of longitudinal traffic barriers subjected to a large truck impact.

While there have been a small number of real-world crash studies specific to large trucks impacting barriers, each are limited either by the age of the data, a reliance on anecdotal crash evidence, or a lack of specific barrier and/or barrier performance information. There is currently no national data available on how well large-truck specific barriers perform when subjected to a real-world large truck impact. Also, it is not known how frequently large trucks impact barriers that are not designed to redirect large vehicles nor how well these barriers perform under these impact conditions. Further, previous research has found that nearly two-thirds of large truck occupant fatalities occurred in single-vehicle crashes in each year between 1975 and 1995 [1] underscoring that roadside safety design is an important facet for this vehicle segment.

OBJECTIVE

The purpose of this study was to investigate real-world large truck impacts into traffic barriers to determine (1) barrier crash and fatal crash involvement rates and (2) the impact performance of barriers not specifically designed to redirect large trucks as well as the real-world performance of large-truck-specific barriers.

BACKGROUND

Full-Scale Crash Testing, Simulation and Existing Large Truck Barriers

Longitudinal barriers must demonstrate satisfactory crashworthiness in a series of full-scale crash tests before being considered acceptable for use on the nation's highways. Procedures for determining the crashworthiness of longitudinal barriers in the US are set forth in NCHRP Report 350 [2] and, more recently, in the Manual for Assessing Safety Hardware (MASH) [3]. Although any new barriers must be developed using MASH [3], barriers satisfactorily tested under NCHRP Report 350 are still considered acceptable for use [4]. Analogous European barrier crash test procedures are prescribed in EN-1317 [5]. These test procedures provide a structure to evaluate barrier crash performance under practical worst-case impact scenarios. Test evaluation focuses on barrier structural adequacy, the post-impact trajectory of the vehicle, and the injury potential for vehicle occupants.

US procedures specify 6 test levels for longitudinal barriers, Test Level 1 (TL-1) through TL-6, each defined by a combination of test vehicles and associated impact conditions [3]. An increase in test level represents an increase in barrier impact performance with TL-6 representing the highest performance level. Barriers tested to a lower test level (TL-1 or TL-2) are generally used on lower volume, lower speed roadways while higher test level (TL-3 and higher) barriers are typically used on higher volume, higher speed roadways such as freeways. Up to and including TL-3, prescribed crash tests involve passenger vehicles only. TL-4 and higher barriers require one heavy vehicle test in addition to TL-3 passenger vehicle tests. The heavy vehicle crash tests prescribed by NCHRP Report 350 and MASH are summarized in Table 1. The primary change for the more recent MASH criteria was an increase in both the mass and impact speed of the single unit truck used in TL-4 test.

Several longitudinal barriers have been developed and crash tested to TL-4 or TL-5 [6]-[20]; these barriers are summarized below in Table 2. With the exception of the Max-Rail, the current TL-5 barriers are concrete barriers. TL-4 barriers include concrete, several high tension cable barriers and a single metal beam barrier. It should be noted that there are numerous bridge rails that also meet TL-4 or TL-5 criteria but have not been included in Table 2. Bridge rails must be developed in accordance with Section 13 of the AASHTO LRFD Bridge Design Specifications [21], which reference NCHRP Report 350 testing procedures [2].

In the development of the higher test level barriers noted above, there has been some limited crash testing experience with heavy vehicles impacting barriers not designed for such impacts (TL-3 or below). Ivey et al. [22] tested both the strong steel post/steel block w-beam barrier and the steel post thrie beam barrier with a 9072-kg school bus. In the thrie beam test, the bus impacting at 89.5 km/hr and an angle of 13.5 degrees was contained and redirected but subsequently rolled one quarter turn on its left side; the barrier performance was judged as marginal. The steel strong post w-beam failed to contain the bus impacting at 96 km/hr and 15 degrees and resulting in rollover and substantial intrusion of the barrier into the passenger compartment. Hirsch [23] provides a more complete listing of heavy vehicle to barrier crash tests, including both higher and lower test level barriers.

Finite element (FE) simulations have been developed and validated to evaluate large truck to barrier impacts, specifically a single unit truck impacting a modified thrie beam barrier [24] and several European test vehicles and barriers [25]. Montella and Pernetti [26] used FE simulation to examine the influence of center of mass and tire-pavement friction on large truck to barrier impacts. Longitudinal position of the center of mass was found to have a large influence on rollover and barrier penetration risk with increasing penetration risk and decreasing rollover risk as the center of mass moves toward the vehicle front. A higher center of mass was found to increase rollover risk but not significantly increase the risk of vaulting over the barrier. The position of the center of mass is also of greater importance for collisions nearing the performance limit of the barrier and in conditions that favor friction.

Large Truck Crash Data Studies and Anecdotal Barrier Performance

A limited number of studies exist specifically relating to real-world large truck crashes involving barriers. Mak and Sicking [27] examined 4,323 police-reported bridge rail crashes occurring in Texas between 1988 and 1990. Approximately 15 percent of the available bridge rail collisions involved heavy vehicles with 75 percent of these impacts involving single unit trucks. The overall bridge rail penetration rate was found to be 4.6 and 15.8 percent for single unit trucks and combination trucks, respectively. When the data set was restricted to newer bridge rails (constructed post-1965), the penetration rates were found to be 2.3 percent for single unit trucks and 7.7 percent for combination trucks. To examine the relationship between trucks and the roadway environment, Jackson [28] compiled data from a number of National Transportation Safety Board (NTSB) large truck crash investigations. The author noted two crashes where a truck climbed a concrete barrier and one crash that involved a truck that penetrated a guardrail, subsequently impacting a bridge support. Based on the available anecdotal evidence, Jackson concludes that barrier installed prior to the early 1970's are ineffective at redirecting large trucks. Michie [29] examined large truck travel trends in light of roadside safety considerations. An examination of travel data from 1970 through 1982 revealed that single unit truck travel increased in both magnitude and percentage (from 16.5 to 23.6 percent) while combination trucks and buses exhibited essentially no growth during that period. Crash data was presented with respect to vehicle and crash type but the data was limited to fixed objects only, with no barrier-specific data present. In general, heavy trucks were found to be overrepresented in rollover, jackknife, and fatal crashes.

Several previous real-world barrier crash data or in-service studies conducted provide anecdotal evidence of barrier performance in large truck impacts. Wiles et al. [30] collected information on concrete median barrier crashes from 25 agencies as part of a large truck concrete median barrier crash testing effort. Of 49 heavy vehicle crashes reported, only 2 instances of barrier penetration were reported. As part of a report on crash testing and field experience of three barriers, Ray and Bryden [31] provide data on two severe large truck impacts to a modified thrie beam barrier on I-70 in Colorado. Both impacts, one with a convoy of single unit trucks and another with a combination truck, resulted in barrier penetration due to impact conditions "well beyond its performance capabilities." Sposito and Johnston [32] note a tractor trailer penetrating a low-tension cable median barrier; this was the only large truck impact out of 53 impacts to the studied median barrier section from December 1996 through March 1998. Martin and Quincy [33] found that approximately 7 percent of heavy vehicles colliding with French median barriers resulted in penetration compared with 0.5 percent for light vehicles impacting median barrier. Seamons and Smith [34] examined median barrier crashes in California from 1984 through 1988. A total of 87 penetrations occurred that involved 49 cable barriers, 17 metal beam barriers, 20 concrete barriers, and 1 thrie beam barrier. Single unit trucks comprised 9 percent of the total number of barrier penetrations while multi-unit trucks comprised 24 percent. For cable, metal beam, and concrete barriers, heavy truck penetrations were approximately 20, 59, and 45 percent of total penetrations for each barrier type, respectively. Based on the proportion of vehicles involved in freeway crashes, heavy vehicle penetrations were found to be overrepresented by a factor of two. Although these studies do provide some anecdotal evidence regarding barrier performance in large truck impacts, all the studies were limited to data within a single state or region within a state and/or country.

METHODOLOGY

The overall approach for this study was to (1) use national level police-reported crash data coupled with aggregate travel data to provide an overall characterization of the large truck to roadside barrier crashes and to (2) use data from an in-depth large truck crash study, augmented with additional roadside information, to determine the performance of barriers in real-world large truck impacts. All data processing and statistical analyses for this study were performed using SAS V9.2 (SAS Institute, Cary, NC).

Data Sources and Case Selection

Overall Characterization of Barrier Crashes

For the overall characterization of crashes involving large trucks and traffic barriers, crash data was selected from the National Automotive Sampling System (NASS) / General Estimates System (GES) and the Fatality Analysis Reporting System (FARS). NASS/GES consists of a nationally representative sample of approximately 50,000 US police-reported crashes per year [35] while FARS provides a census of US motor vehicle fatalities [36]. Aggregate travel data by vehicle type was obtained through the Federal Highway Administration [37]-[38]. As the Michie [29] study provided 1982 travel data, data presented herein will be post-1982.

Cases were selected from NASS/GES from years 2000 through 2009, inclusive. The primary selection criterion was that a vehicle impacted a longitudinal traffic barrier at least once in the event sequence of a particular crash. In terms of NASS/GES coding, one or more of the objects contacted by the vehicle should be coded as 135 or 136 for "guardrail" or "concrete traffic barrier/other longitudinal barrier type." Cases generally fell into one of the following categories: (1) a single vehicle crash where a longitudinal barrier was the only impact, (2) a single vehicle, multi-event crash where a longitudinal barrier was struck at least once in the event sequence, or (3) a multi-vehicle crash where a vehicle struck a longitudinal barrier one or more times in the event sequence.

FARS case selection followed nearly the same general procedure with cases from years 2000 through 2009. Notable exceptions were that the vehicle had to have at least one occupant fatality and that the most harmful event (MHE) for the vehicle was a longitudinal barrier. The latter criterion was used instead of any barrier strike in the event sequence to ensure that the barrier was the primary injury causing impact. Also, FARS data has a finer classification for impacts into longitudinal barriers than NASS/GES. Possible MHE values were guardrail face, guardrail end, concrete barrier, bridge rail, and other barrier. As NASS/GES does not distinguish between bridge rails and bridge structures such as support columns, bridge rails were only included in the FARS analysis.

Barrier Performance in Large Truck Impacts

To determine barrier performance in real-world large truck impacts, data were obtained from the Large Truck Crash Causation Study (LTCCS). The LTCCS provides detailed information for approximately 1,000 large truck crashes that occurred in the U.S. between 2001 and 2003 [39]. To be included as a case in LTCCS, a crash had to involve at least one vehicle with gross vehicle weight in excess of 10,000 lbs and result in a fatality or injury [39]. Cases selected only included large trucks that impacted at least one longitudinal barrier during the sequence of events for that particular vehicle. For the purpose of this sub-study, a longitudinal barrier included roadside, median barriers, end terminals, and bridge rails.

Database Development

As the LTCCS does not contain detailed barrier data, scene photographs and scene diagrams for each suitable case were examined to ascertain variables of interest. Methodology for augmenting the existing LTCCS data with roadside specific barriers is similar to previous procedures outlined by Gabauer and Gabler [40] and Gabauer [41] for augmenting the National Automotive Sampling System (NASS) / Crashworthiness Data System (CDS). For each suitable LTCCS case, the following additional data was determined:

1. <u>Barrier Type and Location</u>: An attempt was made to classify each barrier to the fullest extent possible based on the available scene photographs. This data was then used to classify the barrier by lateral stiffness into 3 categories: (1) flexible, (2) semi-rigid, and (3) rigid based on the Roadside Design Guide [42] classification scheme. Location of the barrier was also noted with respect to the roadway cross section, e.g. barriers located in the median were differentiated between those located on the roadside.
2. <u>Barrier Test Level</u>: Using the available photographs, the NCHRP 350 test level (TL) of each crash-involved barrier was determined. Barriers were classified into one of 4 categories: (1) TL-2, (2) TL-3, (3) TL-4, or (4) TL-5+.
3. <u>Barrier Performance</u>: For each crash, an assessment of the barrier crash performance for the initial barrier impact was made using the available data. Performance was classified into one of 2 categories: no penetration, or penetration. Any cases where penetration was not able to be discerned were excluded from further analysis.
4. <u>Impact Location Relative to Barrier</u>: Based on the available scene diagram and photos, a determination was made as to whether the vehicle impacted the end of the barrier or the length of need (portion between the end terminals).

The additional data was imported into SAS as a barrier specific table so that it could be readily merged with the LTCCS tables of interest.

Data Analysis

Characterization of Large Truck Barrier Crashes

For each year of available data, the total number of police-reported barrier impacts was estimated using the available NASS/GES data. As NASS/GES is a sample of all police-reported crashes, weights must be applied to generate nationally representative estimates. These weights are provided for each case in NASS/GES and were used to generate the national estimates. The estimated crashes were then categorized by the type of vehicle impacting the barrier using the BODY_TYP variable available in NASS/GES. Vehicle type was split into 5 categories: (1) cars including motorcycles, (2) light trucks including light pickups, vans and sport utility vehicles, (3) buses, (4) single unit trucks, and (5) combination trucks. These categories were selected to match the aggregate travel data categories available from the FHWA. The data for each vehicle type and year combination was then normalized by the associated amount of vehicle miles traveled. The non-heavy vehicle crash rates were included to serve as a means of comparison.

Using the FARS data for each corresponding year, the total number of fatalities was computed for barrier crashes where the barrier was identified as the most harmful event for the subject vehicle. These data were also normalized by the corresponding vehicle miles traveled to produce fatality rates per 100 million vehicle miles traveled for each year and vehicle type combination. Aggregate vehicle travel data was also examined separately to identify vehicle type trends between 1983 and 2008. Note that vehicle travel data was not currently available for 2009 from the FHWA.

Barrier Performance in Large Truck Impacts

Using the suitable LTCCS cases, a binary logistic regression model was developed to predict barrier penetration based on barrier type/test level, while accounting for confounding factors including truck type and presence of a non-collision event or impact before barrier strike. For the purposes of the model, barrier test level (TL) was consolidated into three categories: TL-3 and below, TL-4, and TL-5+. Truck type was coded as a dichotomous variable: tractor trailer or single unit truck type. Presence of a non-collision (e.g. jackknife or rollover) prior to barrier impact was another dichotomous variable (yes or no) that was determined using the available event data in the LTCCS. Similarly, the presence of an impact prior to the barrier collision was dichotomous. Note that end terminals were excluded from the barrier penetration model as some terminals are designed to permit vehicle penetration.

Odds ratios were used to compare barrier penetration risk by barrier test level as well as quantify the effects of the possible confounding factors. Although the LTCCS uses a complex sampling design, the available weights were not used due to questions regarding the validity of national estimates generated from these weights, especially for single-vehicle crashes [43]. The associations shown herein are valid for serious truck crashes but no estimate of the national population was made. A comparison, however, is made between the total weighted NASS/GES large truck impacts occurring between 2001 and 2003 and the predicted number from the available LTCCS data.

RESULTS

Characterization of Large Truck Barrier Crashes

Based on the case selection criteria, there were 31,882 raw NASS/GES cases available representing approximately 2.2 million vehicles impacting longitudinal barriers. There were a total of 8,203 fatalities due to crashes where a longitudinal barrier was the most harmful event in the crash. Table 3 summarizes the available barrier crash and fatality data from NASS/GES and FARS. Large trucks appear to be equally represented in both police reported and fatal crashes with combination trucks slightly overrepresented in terms of barrier-related fatalities (2.5 percent of fatalities and 2.2 percent of police reported barrier crashes).

For each vehicle type, the left portion of Figure 1 shows the police-reported barrier crash involvement rates between years 2000 and 2008. The right portion of Figure 1 is a similar plot showing barrier crash fatality rate from 2000 through 2008. In both plots, the rates were normalized based on available vehicle travel data for the corresponding crash year. For most vehicle types, both the barrier crash rate and fatality rate were reasonably static over the studied time period. A notable exception was the combination truck, which appear to have a slight decreasing trend. The overrepresentation of combination trucks in terms of fatality rate is evident as the fatality rate is approximately equal to that of the LTV segment, but LTVs are roughly twice as likely to be involved in a barrier crash as a combination truck.

Table 4 summarizes the available FHWA vehicle travel data for 1983, one year subsequent to the Michie study [29], as well as 2008, the most recent year of data available. Over this period, all vehicle types saw an increase in vehicle miles traveled with the largest increase in the light truck category experiencing roughly a four-fold increase in miles traveled. The second and third largest increases, however, were realized in the single unit truck and combination truck sectors; vehicle miles traveled in both of these vehicle types nearly doubled.

Barrier Performance in Large Truck Impacts

Based on the selection criteria, there were a total of 155 LTCCS cases suitable for analysis. Table 5 provides a summary of the characteristics of the available barrier crash cases. Flexible barriers included four cable and 4 weak post w-beam barriers. All cable barriers present were generic low-tension three-cable barrier and all but one case resulted in vehicle penetration. Semi-rigid barriers were primarily strong post w-beam barriers (85 percent) with the remainder being strong post thrie beam (14 percent; including one bridge rail) and a single box beam barrier. Rigid barriers were primarily concrete barriers (93 percent) with the remainder being bridge rails (7 percent). Penetration rates for the midsections of barriers designed to contain large trucks (TL-4+) was 17 percent compared to approximately 50 percent for barriers not designed for large trucks (TL-2, TL-3). In terms of the truck specific barriers, TL-4 barriers had a 22 percent penetration rate while the TL-5 barriers had no penetrations. Note that all of the TL-4 barrier penetrations involved tractor-trailer vehicles. For all barrier test levels, the majority of the impacting vehicles were tractor-trailer configurations (75 percent). Nearly three quarters of the impacting vehicles had a curb weight between 5,000 and 9,000 kg. A limited amount of roadway data was available, including roadway functional classification, and has also been summarized in Table 5. Application of the available LTCCS statistical weights resulted in an estimate of 15,611 large truck barrier impacts occurring from 2001 through 2003.

After exclusion of the 20 end terminal cases, a binary logistic regression model was developed to predict barrier penetration. The developed model had a C-statistic value of 0.77 representing the area under the Receiver Operator Characteristic (ROC) curve. This value provides a single numerical value of how well the model distinguishes between the response variable, in this case, presence of barrier penetration. Barrier type was the only variable found to have a statistically significant effect on barrier penetration. The odds ratio values obtained from the binary logistic regression are summarized in Table 2.

Note the odds ratio shown is with respect to the group indicated in the comparison group column. The 95 percent confidence bounds on each odds ratio are also shown. Note that the odds ratio for TL-5+ barriers compared to TL-3 or below barriers was not included as there were no penetrations observed in the available data for TL-5+ barriers and thus a valid odds ratio could not be estimated. There was some evidence of decreased barrier penetration risk for tractor trailers, barrier impacts not preceded by any other collision event, median barrier impacts, and trucks that roll or jackknife prior to barrier impact; these results, however, were not found to be statistically significant. Large truck barrier penetration risk was found to decrease by a factor of approximately 4 for impacts with TL-4 barriers compared to a barrier tested to TL-3 or lower. Grouping the TL-4 and TL-5 barriers into a single category (model results not shown) results in a decrease in large truck barrier penetration risk by a factor of approximately 6.

DISCUSSION

Available vehicle travel data suggests that large trucks continue to represent a growing segment of the fleet, second only to light trucks such as pickups, sport utility vehicles, and light-duty vans. Although recent research [1] suggests that single vehicle crashes present a higher risk for heavy trucks, this does not appear to be the case with longitudinal barrier impacts. Large truck impacts with a longitudinal barrier comprise approximately 3 percent of all police-reported longitudinal barrier impacts and roughly the same proportion of longitudinal barrier fatalities. Only combination trucks appear to be slightly overrepresented with respect to longitudinal barrier fatalities. Barrier crash involvement and fatality rates by vehicle type appear to relatively stable over the past 10 years despite combination trucks demonstrating a slight decreasing trend in both barrier crash and fatality involvement by vehicle miles traveled.

Although perhaps not surprising, the logistic regression model results support the notion that large trucks impacting a higher test level barrier are less likely to penetrate the barrier. Large trucks impacting a TL-4 barrier were found to be approximately 4 times less likely to penetrate the barrier than if the impacted barrier was TL-3 or lower. When all large-truck specific barriers were combined into a single category, large trucks were found to be 6 times less likely to penetrate the barrier. Of the 16 TL-5+ barriers present in the available data, there were no instances of large truck penetration. Approximately 17 percent of the large truck impacts with TL-4+ barriers, however, did result in barrier penetration. This is higher than the anecdotal evidence collected based on the real-world crash and in-service studies noted above. The bias in LTCCS toward more severe crashes may account for some of this discrepancy. Without a nationally representative estimate, however, it is unclear whether this estimate is indeed artificially high. A comparison between the LTCCS with the weights applied (15,611 large truck impacts) to the NASS/GES-estimated crashes occurring from 2001 through 2003 (21,496 impacts) revealed that the LTCCS estimate was approximately 25 percent low. Although large truck penetration risk was found to be 4 to 6 times higher for impacts with TL-3 and lower barriers, it is interesting to note that these barriers were able to redirect large trucks half of the time.

CONCLUSIONS

This study provides a focused assessment of longitudinal performance for large truck impacts based on in-depth real-world crash data. Although large-truck-specific barriers were found to perform better than non-heavy vehicle specific barriers, there is still room for improvement. The 17 percent penetration rate is especially a concern because the higher test level barriers are designed to protect other road users, not the occupants of the large truck. Surprisingly, barriers not specifically designed for large truck impacts were found to prevent large truck penetration approximately half of the time. This suggests that adding costlier higher test level barriers may not always be warranted, especially in areas with lower truck volumes.

ACKNOWLEDGEMENTS

The author gratefully acknowledges Clare McLaughlin for her help with reviewing the LTCCS cases.

REFERENCES

[1] Cerelli, E.C. Trends in Large Truck Crashes, NHTSA Technical Report DOT-HS 808 690, Springfield VA, 1998.

[2] Ross, Hayes E., Sicking, D.L., Zimmer, R.A., and J.D. Michie. *Recommended Procedures for the Safety Performance Evaluation of Highway Features*. NCHRP Report 350, TRB, National Research Council, Washington, D.C., 1993.

[3] American Association of State Highway and Transportation Officials (AASHTO). Manual for Assessing Safety Hardware, 2009.

[4] Nicol, D.A. Information: Manual for Assessing Safety Hardware, Memorandum, US Department of Transportation, Federal Highway Administration, November 20, 2009.

[5] European Committee for Standardization (CEN). *Road Restraint Systems – Part 2: Performance Classes, Impact Test Acceptance Criteria and Test Methods for Safety Barriers*. European Standard EN 1317-2. 2010.

[6] Horne, D.A. Report 350 Nonproprietary Guardrails and Median Barriers, Memorandum HMHS-B64, US Department of Transportation, Federal Highway Administration, February 14, 2000.

[7] Ray, M. H. and Richard G. McGinnis. Synthesis of Highway Practice 244: Guardrail and Median Barrier Crashworthiness. Transportation Research Board, National Research Council, Washington, D.C., 1997.

[8] Buth, C. Eugene and Wanda L. Menges. NCHRP Report 350 Test 4-12 of the Modified Thrie Beam Guardrail. Report FHWA-RD-99-065, US Department of Transportation, Federal Highway Administration, December 1999.

[9] Buth, C.E., Hirsch, T.J., and C.F. McDevitt. Performance Level 2 Bridge Railings. In *Transportation Research Record 1258*, TRB, National Research Council, Washington, DC, 1990.

[10] Mak, K.K., Gripne, D.J., and C.F. McDevitt. Single Slope Concrete Bridge Rail. In *Transportation Research Record 1468*, TRB, National Research Council, Washington, DC, 1994.

[11] Baxter, J.R. [Letter for Brifen Wire Rope Safety Fence NCHRP 350 Acceptance]. HSA-10/B-82B, March 27, 2005.

[12] Rice, G.E. [Letter for Safence NCHRP 350 Acceptance]. HSSD-10/B-88E, July 31, 2007.

[13] Baxter, J.R. [Letter for Gibraltar Cable Barrier NCHRP 350 Acceptance]. HSA-10/B-137A1, October 27, 2006.

[14] Baxter, J.R. [Letter for Trinity CASS NCHRP 350 Acceptance]. HSSD/B-157, April 23, 2007.

[15] Nicol, D.A. [Letter for Nucor Four-Cable Wire Rope Barrier for TL-4 NCHRP 350 Acceptance]. HSSD/B-167, January 24, 2008.

[16] Alberson, D.C., Zimmer, R.A., Menges, W.L., NCHRP Report 350 Compliance Test 5-12 of the 1.07 m Vertical Wall Bridge Railing, Report to Federal Highway Administration, Texas Transportation Institute, February 1996.
[17] Buth, C.E., Campise, W.L., Griffith, L.I., Lowe, M.L., and D.L. Sicking. Performance Limits of Longitudinal Barriers, FHWA-RD-86-154, Federal Highway Administration, Washington, DC, 1986.
[18] Mak, K.K., and W.L. Campise. Test and Evaluation of Ontario "Tall Wall" Barrier with an 80,000-Pound Tractor-Trailer. Ontario Ministry of Transportation, Toronto, Ontario, Canada, 1990.
[19] Lechtenberg, K.A., Bielenberg, R.W., Rosenbaugh, S.K., Faller, R.K. and D.L. Sicking. High-Performance Aesthetic Bridge Rail and Median Barrier. In *Transportation Research Record 2120*, 2009, pp 60-73.
[20] Baxter, J.R. [Letter for Composite Structural Design Max-Rail NCHRP 350 Acceptance]. HSA-10/B-142, January 12, 2006.
[21] American Association of State Highway and Transportation Officials (AASHTO). AASHTO LRFD Bridge Design Specifications, 5th edition, 2010.
[22] Ivey, D.L., McDevitt, C.F., Robertson, R., Buth, C.E., and A.J. Stocker. Thrie-Beam Guardrails for School and Intercity Buses. In *Transportation Research Record 868*, 1982, pp 38-44.
[23] Hirsch, T. J. Longitudinal Barriers for Buses and Trucks. In *Transportation Research Record 1052*, TRB, National Research Council, Washington, D.C., 1986, pp 95-102.

[24] Cansiz, O.F. and A.O. Atahan. Crash Test Simulation of a Modified Thrie-Beam High Containment Level Guardrail under NCHRP Report 350 TL 4-12 Conditions. *International Journal of Heavy Vehicle Systems 2006*, Vol. 13, No. 1, pp. 2-18.
[25] Borovinsek, M., Vesenjak, M., Ulbin, M., and Z. Ren. Simulation of Crash Tests for High Containment Levels of Road Safety Barriers. *Engineering Failure Analysis* 14 (2007) 1711-1718.
[26] Montella, A. and M Pernetti. Heavy-Goods Vehicle Collisions with Steel Road Safety Barriers: Combined Influences of Position of Center of Mass and Tire-Pavement Friction. In *Transportation Research Record 1690*, 1999, pp 84-94.
[27] Mak, K.K. and D.L. Sicking. Analysis of Bridge Railing Accidents. In *Transportation Research Record 1468*, TRB, National Research Council, Washington, DC, 1994, pp 19-24.
[28] Jackson, L.E. Truck Accident Studies. In *Transportation Research Record 1052*, TRB, National Research Council, Washington, D.C., 1986, pp 137-145.
[29] Michie, J.D. Large Vehicles and Roadside Safety Considerations. In *Transportation Research Record 1052*, TRB, National Research Council, Washington, D.C., 1986, pp 90-95.
[30] Wiles, E.O., Bronstad, M.E., and C.E. Kimball. Evaluation of Concrete Safety Shapes by Crash Tests with Heavy Vehicles. In *Transportation Research Record 631*, 1977, pp 87-91.
[31] Ray, M.H. and J.E. Bryden. Summary Report on Selected Guardrails. Report No. FHWA-SA-91-050, US Department of Transportation, Washington, DC, June 1992, 39 p.
[32] Sposito, B and S. Johnston. Three-Cable Median Barrier Final Report. Report OR-RD-99-03, Oregon Department of Transportation, July 1998.
[33] Martin, J.L., and R. Quincy. Crossover Crashes at Median Strips Equipped with Barriers on a French Motorway Network. In *Transportation Research Record 1758*, TRB, National Research Council, Washington, D.C., 2001, pp 6-12.
[34] Seamons, L. L., and R. N. Smith. Past and Current Median Barrier Practice in California. Report CALTRANS-TE-90-2. California Department of Transportation, Sacramento, 1991.
[35] US Department of Transportation. *National Automotive Sampling System General Estimates System: Analytical User's Manual 1988-2009*. DOT HS 811 355. August 2010. 278 pages.
[36] US Department of Transportation. *FARS Analytic Reference Guide 1975 to 2009.* DOT HS 811 352. August 2010. 456 pages.
[37] Office of Highway Information Management. *Highway Statistics Summary to 1995*. Federal Highway Administration, Washington, DC, 1997.
[38] Office of Highway Information Management. *Highway Statistics Series*. Federal Highway Administration, Washington, DC, 1996-2009.
[39] Large Truck Crash Causation Study Analytical User's Manual Federal Motor Carrier Safety Administration (FMCSA); National Highway Traffic Safety Administration (NHTSA). US Department of Transportation, June 2006. 513 pages.
[40] Gabauer, D.J. and H.C. Gabler. Differential Rollover Risk in Vehicle-to-Traffic Barrier Collisions. Ann Adv Automot Med. 2009 Oct; 53: 131-40.

[41] Gabauer, D.J. Secondary collisions following a traffic barrier impact: frequency, factors, and occupant risk. Ann Adv Automot Med. 2010; 54: 223-32.
[42] American Association of State Highway and Transportation Officials (AASHTO). AASHTO Roadside Design Guide, 3rd edition, 2002, 344 p.
[43] Blower D. and Green P.E. Truck Mechanical Condition and Crashes in the Large Truck Crash Causation Study. UMTRI-2009-09, University of Michigan Transportation Research Institute, March 2009, 77 pages.

List of Tables

List of Figures

Table 1. Summary of Large Truck Crash Test Vehicles and Impact Conditions

Crash Test Specification	Vehicle Designation /Type	Vehicle Mass [kg]	Impact Speed [kph]	Impact Angle [°]	Test Level
NCHRP Report 350 [2]	8000S/ Single Unit Truck	8,000	80	15	TL-4
	36000V/ Van Tractor Trailer	36,000	80	15	TL-5
	36000T/ Tanker Tractor Trailer	36,000	80	15	TL-6
MASH [3]	10000S/ Single Unit Truck	10,000	90	15	TL-4
	36000V/ Van Tractor Trailer	36,000	80	15	TL-5
	36000T/ Tanker Tractor Trailer	36,000	80	15	TL-6

Table 2. Summary of TL-4 and TL-5 Longitudinal Barriers

NCHRP Report 350 Test Level	Barrier (AASHTO Designation, if applicable)	Reference(s)
4	Strong Post Thrie Beam Barrier (SGR09b; SGM09b)	[6] [7] [8]
	810-mm NJ Safety Shape Median Barrier (SGM11a)	[6] [7]
	810-mm F-Shape Median Barrier (SGM10a)	[6] [7] [9]
	810-mm Vertical Concrete Barrier	[6]
	810-mm Constant Slope Barrier	[6] [7] [10]
	Brifen WRSF	[11]
	Safence 3-Cable/4-Cable	[12]
	Gibralter 3-Cable/4-cable	[13]
	Trinity CASS TL-4	[14]
	Four-Cable Nucor Wire Rope Barrier System	[15]
5	1070-mm NJ Safety Shape Median Barrier (SGM11b)	[6] [17]
	1070-mm F-Shape Median Barrier (SGM10b)	[6]
	1070-mm Vertical Concrete Barrier	[6] [16]
	1070-mm Constant Slope Barrier	[6]
	1070-mm Ontario Tall Wall Barrier (SGM12)	[6] [7] [18]
	1067-mm High Performance Aesthetic MwRSF Barrier	[19]
	1150-mm Max-Rail	[20]

Table 3. Available National Level Barrier Crash Data [NASS/GES and FARS; 200-2009, inclusive]

Variable	Category	NASS/GES			FARS	
		Raw	Weighted	Weighted %	Raw	%
All	N/A	31,882	2,219,650	100	8203	100
Crash Type	Single Vehicle	21,023	1,757,124	79	7302	89
	Multiple Vehicle	10,859	462,526	21	901	11
Vehicle Type	Car	19,487	1,404,447	63	5898	72
	LTV	9,327	747,804	34	2033	24.8
	Bus	30	2,512	0.1	11	0.1
	Single Unit Truck	817	15,102	0.7	52	0.6
	Combination Truck	2,221	49,785	2.2	209	2.5

Table 4. Vehicle Miles Traveled [Billions] by Vehicle Type [37]-[38]

Year	Passenger Cars	Light Trucks	Buses	Single Unit Trucks	Combination Trucks	All Passenger Cars	Heavy Vehicles
1983	1204	328	5.2	42.5	73.6	1537	116
2008	1630	1109	7.1	84.0	143.5	2746	227
% Increase	**35**	**238**	**36**	**97**	**95**	**79**	**96**

Table 5. Summary of Suitable Barrier Crash Cases in the LTCCS Database

Variable	Category	Raw Cases
Vehicle Involvement	Single Vehicle Multiple Vehicle	95 60
Barrier Type	Flexible Semi-Rigid Rigid	8 78 69
Barrier Test Level	TL-2 TL-3 TL-4 TL-5+	7 82 50 16
Component Struck	Length of Need (Midsection) End Terminal	135 20
Vehicle Type	Truck (> 4,536 kg) Tractor-Trailer(s)	38 117
Vehicle Curb Weight	≤ 5,000 kg 5,001 kg – 7,000 kg 7,001 kg – 9,000 kg 9,001 kg – 11,000 kg >11,000 kg Unknown	8 52 62 7 10 16
Barrier Performance	Vehicle Penetration Vehicle Containment	55 100
Roadway Functional Classification	Principal Arterial Minor Arterial Collector/Local	136 8 11
Urban/Rural	Urban Rural	104 51

Table 6. Summary of Odds Ratio Results for the Barrier Penetration Binary Logistic Regression Model

Parameter	Value	Comparison Group	Odds Ratio	95% CI
Barrier Type	TL-4	TL-3 or below	0.23	0.1 - 0.6
Vehicle Type	Tractor Trailer(s)	Single Unit Truck	0.82	0.3 – 2.1
Non-Collision Before Barrier Impact	Present	Not Present	0.44	0.2 – 1.1
Barrier Location	Median	Roadside	0.81	0.3 – 1.9
Impact Before Barrier Impact	Not Present	Present	0.51	0.2 – 1.3

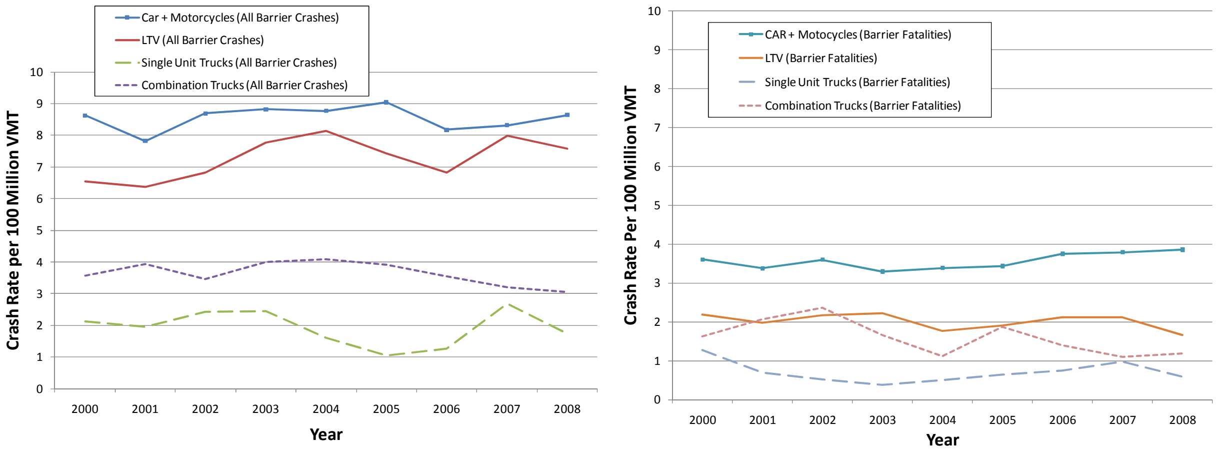

Figure 1. Police-Reported Barrier Crash Rates (left) and Barrier Crash Fatalities per 100 Million VMT by Vehicle Type and Year [NASS/GES and FARS; 2000-2009, inclusive; FHWA Table VM-1]