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TechBrief

Possible Methodology for Probabilistic Assessment of Bridge Safety Against Vehicular Collisions

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This document is a technical summary of the George Washington University report, *Possible Methodology for Probabilistic Assessment of Bridge Safety Against Collisions*, available at https://rosap.ntl.bts.gov/view/dot/74439. This report is a deliverable from a research study sponsored by the Federal Highway Administration (FHWA).

Introduction

This study outlines a possible stochastic methodology for identifying bridges with greater probability of failure from vehicular collisions. This methodology will account for the stochastic nature of the following variables:

- Speed and weight of trucks.
- Frequency of heavy truck collisions at a given bridge location and its direct impact on bridge safety.
- Stochasticity of impulse loading functions for the intensity of heavy truck collisions at bridge piers.
- Strain rate effects on material properties from the resulting collisions.

Traffic and collision data were used to develop Poisson-based probability functions for evaluating the probability of bridge failure. In this report, bridge failure represents total collapse—when one or more spans of a bridge's superstructure has lost support of its substructure due to either the damage or destruction of the substructure or the superstructure being displaced off of the substructure. The established Poisson-based probability functions can support estimating the likelihood of bridge failure using stochastic models. These models are used to assess the vulnerability and mitigation of bridge elements and systems subjected to the impact of heavy trucks. Given the on-site availability of traffic data, 17 bridges were selected from the commonwealth of Virginia to form a test-bed study site.

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Researchers — This work was conducted by George Washington University under the direction of Dr. Pedro F. Silva, Dr. Samer H. Hamdar, Dr. Sameh S. Badie, and Dr. Pan Dong. The work was performed under contract 693JJ321C000031.

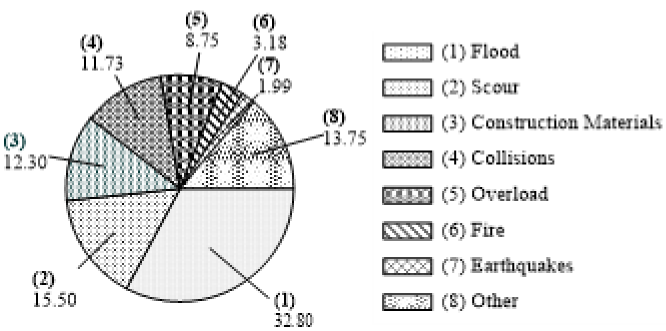
Key Words — truck collisions, truck speed distribution, truck weight distribution, probability of bridge failure, frontal collisions, parametric pulse functions, strain rate effects.

Scope

The methodology described in Silva et al. (2024) presents a possible stochastic methodology for quantifying the probabilistic failure of a bridge subjected to heavy truck collisions. This methodology includes the stochastic nature of vehicular collisions and its ensuing impact on the safety of bridges. Stochastic models were formulated for estimating the probability of bridge failure.

Background

A literature review focused mainly on design and construction of bridges against heavy truck collisions and the severity of traffic collisions. As shown in Figure 1, around 20 percent of bridge failures were attributed to vehicular collisions or vehicles exceeding posted weight limits (Wardhana and Hadipriono 2003).



Note: Original data source Wardhana and Hadipriono (2003)
Source: FHWA
Figure 1. Charts. Bridge failures between 1989 and 2000.

This report analyzes data from the National Bridge Inventory (NBI), from the FHWA Long-Term Bridge Performance (LTBP) InfoBridge™, and the National Highway Traffic Safety Administration (NHTSA) Traffic Safety Facts Annual Report.

According to the NHTSA 2019 Traffic Safety Facts Annual Report (2021), there were 6,756,000 police-reported crashes in the United States in 2019. This marks the second highest in the 2010s. Among these crashes, less than 1 percent (33,244 collisions) were fatal, 28 percent (1,916,000) resulted in a non-fatal injury, and 71 percent (4,806,000) were classified as property-damage only with no reported injuries. Since 1966, crash, fatality and injury rates consistently decreased until the 2010s. During the 2010s, these rates either decreased slightly or remained nearly constant regardless of the countermeasures deployed.

The data from NHTSA (2021) also shows that since 2013, approximately 15,000 vehicular collisions involving bridges in the United States have occurred each year. As truck travel and accidents continue to increase the need to protect more bridge structures against heavy traffic collisions will continue to increase.

Research Objectives

The stochastic methodology proposed in this study identifies strategic solutions to increase the safety of bridges according to the following research objectives:

- Evaluate the resiliency of bridge superstructures against overhead collisions.
- Evaluate the resiliency of bridges from frontal collisions on bridge substructures.
- Evaluate the resiliency of bridges against fires resulting from collisions.
- Evaluate potential cascading effects and disproportionate collapse resulting from heavy truck collisions.
- Estimate the likelihood of a collision resulting in a fire event with high consequences.
- Develop a stochastic methodology for quantifying the probability of failure of bridges.

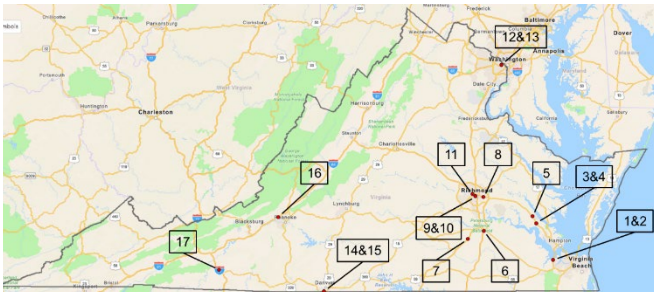
Test Bed Study Site

In this study, 17 bridges were selected to form a test bed study site to investigate the analytical and econometric approaches developed in this research program. Stochastic models for traffic density were developed from over 700 active traffic detector stations placed along the Virginia roadway network.

Based on the spatial pairing between bridges in Virginia and traffic detector stations, these 17 study sites shown in Figure 2 with the following characteristics:

- A bridge intersecting a roadway segment with bridge pier elements exposed to traffic under the bridge.
- The roadway segment is monitored by a detector station with vehicle classification within 0.1 miles from the intersection of the bridge and the roadway.
- The bridge piers are not protected by concrete barriers with a height greater than 24 inches.

Figure 3 illustrates study site 7. The 17 study sites are described in detail in Silva et al. (2024).



Data overlay on Original Map: Google Earth Toolbox®[1] MATLAB[1]. Source: FHWA

Figure 2. Illustration. Map of the 17 study sites.

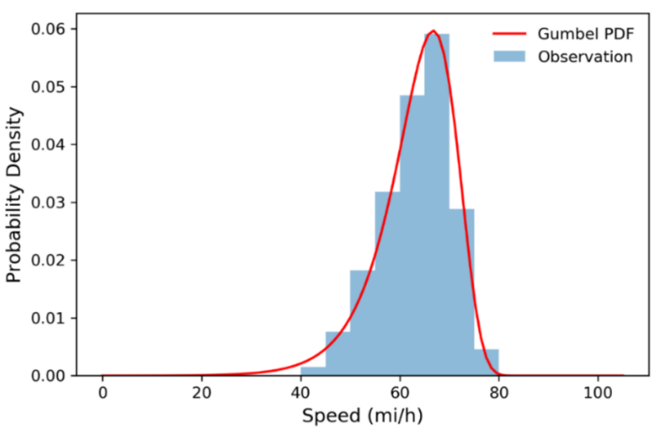
Source: FHWA

Figure 3. Illustration. Isometric view of study site 7.

Heavy Truck Collisions

Speed Distribution

Vehicle speeds observed at a specific location during a one-hour period may follow the Extreme Value Type I distribution, often designated as a Gumbel distribution.



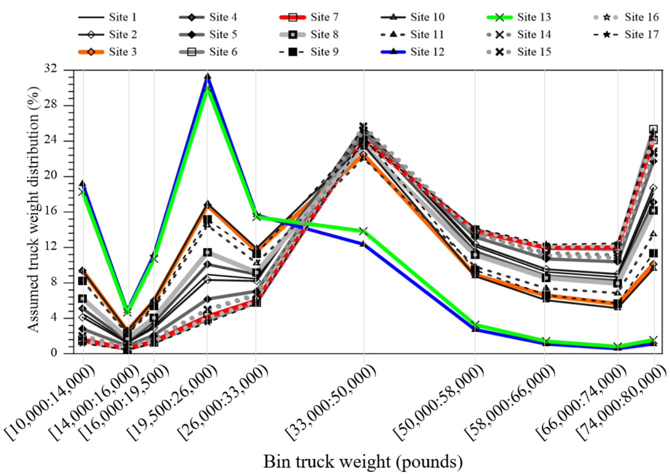
Source: FHWA

Figure 4. Graph. Gumbel-distributed vehicle speed of test bed study site No. 15, where the speed limit is 65 mph.

As illustrated in Figure 4, the observed distribution of vehicle speeds is asymmetric and more left-tailed given the posted speed limit. The left-tailed (or maximum-type) Gumbel distribution may capture this asymmetry.

Weight Distribution

The New York City (NYC) Weigh-in-Motion (WIM) OpenData (NYC WIM, 2024) provides axle weight and gross vehicle weight data from sensors installed on all six lanes of the Brooklyn-Queens Expressway at Pearl Street, Brooklyn from 2019 to 2024. These types of sensors have not yet been installed in Virginia. Market share statistics from the data were combined with the annual average truck traffic volumes at the study sites to develop an assumed truck weight for the 17 study sites, presented in Figure 5. While the NYC WIM data does not provide data for the truck weight distributions for the study sites in VA, it can serve as an example of data that a traffic study could produce.



Source: FHWA

Figure 5. Graph. Truck weight distributions at study sites.

Truck-Related Collision Involvement Rate

Traffic detector stations at the 17 test bed study sites were queried to estimate the truck-related collision involvement rate, Φ_T, which represents truck-related collisions per million truck miles traveled as follows:

$$\Phi_T = \frac{\sum \hat{N}_i}{\sum \hat{V}_i \cdot L_i} \times 1{,}000{,}000 = 0.7626$$

Figure 6. Equation. Truck-related collision involvement rate.

In Figure 6, $\hat{N}_i$ denotes the number of truck-related collisions occurring on Link i, $\hat{V}_i$ denotes the volume of trucks traversing Link i, and L_i denotes the length of Link i in miles. In total, 402 links were examined, accounting for 1103 miles of roadways of the Virginia network. In total, $\sum \hat{N}_i$, 756 truck-related collisions were

[1] The U.S. Government does not endorse products or manufacturers. They are included for informational purposes only and are not intended to reflect a preference, approval, or endorsement of any one product or entity.

identified on these links over roughly one billion truck miles traveled from 2011 to 2016.

Expected Annual Number Collisions

The expected annual number of truck-related collisions that would occur under the bridge is obtained by multiplying the involvement rate, Φ_T, by the bridge width, W_b, and the estimated annual truck volume traversing under the bridge. The expected annual number of truck-related collisions, λ, is estimated by:

$$\lambda = \left(\frac{\hat{V}}{1{,}000{,}000}\right)\left(\frac{W_b}{5280}\right)\Phi_T$$

Figure 7. Equation. Expected annual truck-related collisions.

In Figure 7, $\hat{V}$ denotes the annual truck volume traversing under the bridge and W_b denotes the width of the bridge in feet. Figure 7 indicates the number of truck-related collisions that may occur under bridges; however, it does not directly provide a measure of collisions to bridge piers. Therefore, it helps to refine the collision frequency Φ_T to evaluate the extent to which the bridges are exposed to collisions.

This is achieved by multiplying Φ_T by a conditional probability of the likelihood of under-bridge truck-related collisions colliding into bridge piers. This conditional probability may be estimated by a Monte Carlo simulation that considers various endogenous (e.g., the weight and speed of trucks) and exogenous factors (e.g., the type of protection for bridge piers and the roadway geometric under bridges).

Probability of Bridge Failure

Data from traffic detectors and transportation accident reports in Virginia show that truck-related collisions can be assumed to: (1) follow a Poisson distribution, and (2) occur independently of time at a constant rate. The probability of bridge failure for a specific bridge in T years with unidirectional roadway under the bridge was formulated as follows:

$$\mathrm{Pr}_{bf} = 1 - \sum_{k=1}^{Z} \left\{ \begin{array}{c} \dfrac{(\lambda T)^k e^{-\lambda T}}{k!} \\ \cdot\,[1 - \mathrm{Pr}(Q|C)]^k \end{array} \right\}$$

Figure 8. Equation. Probability of bridge failure in T years with a unidirectional roadway under the bridge.

Where k denotes the number of truck-related collisions in a bridge link, λ is the expected annual number of truck-related collisions in a bridge link and $Pr(Q|C)$ denotes the probability of bridge failure due to a specific truck-related collision given the weight and speed distribution of trucks and the width of the pier.

Similarly, the probability of bridge failure for a specific bridge in a year with bidirectional roadway under the bridge can be formulated as follows:

$$\mathrm{Pr}_{bf} = 1 - \sum_{k_1=1}^{Z} \sum_{k_2=1}^{Z} \left\{ \begin{array}{c} \left(\dfrac{\lambda^{k_1} e^{-\lambda_1}}{k_1!}\right) \cdot \left(\dfrac{\lambda^{k_2} e^{-\lambda_2}}{k_2!}\right) \\ \cdot\,[1 - \mathrm{Pr}_1(Q|C)]^{k_1} \\ \cdot\,[1 - \mathrm{Pr}_2(Q|C)]^{k_2} \end{array} \right\}$$

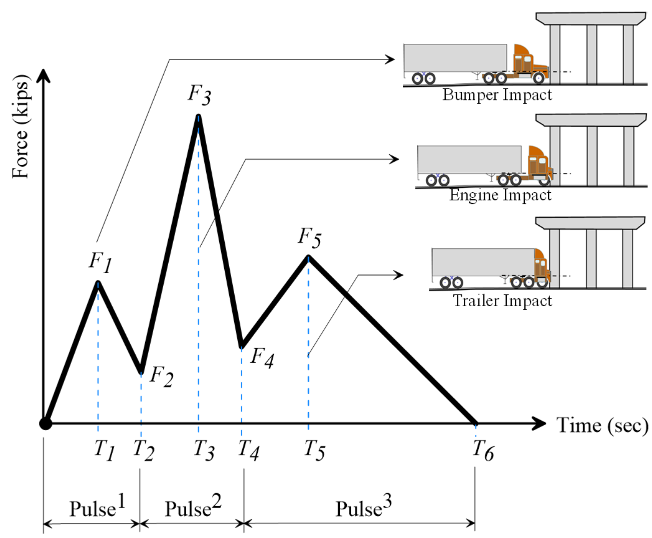
Figure 9. Equation. Equation. Probability of bridge failure in a year with a bidirectional roadway under the bridge.

Where 1 and 2 in Figure 9 corresponds to the bidirectional directions. In these equations, the probability of bridge failure, Pr_{bf}, can be estimated during the service life of a bridge and used as to evaluate the safety of a bridge at a specific location.

These equations estimate the probability of such events rather than the expected frequency, as bridge failures induced by collisions may not be observed during the testing period at a specified location. The probability of collision can be established over an extended period of time, which may correspond to the bridge service life.

Stochasticity of Impulse Loading Function

Agrawal et al. (2018) proposed the parametric pulse function shown in Figure 10.



[1] Bumper impact, [2] Engine impact, and [3] Trailer impact.
Data source: Cao et al. (2020), Source: FHWA

Figure 10. Illustration. Pulse function for frontal collisions.

The following parameters were considered in developing stochastic models for the pulse functions:

- The vehicular speed, $\overline{V}$, is a random variable with an assumed Gumbel distribution.
- The vehicular weight, $\overline{W}$, follows the assumed weight distributions outlined in Figure 5.
- The bridge pier width, $\overline{b}$, is a normal random variable with an assumed coefficient of variation of 2 percent.

This pulse function is used in this study for calculating peak dynamic forces resulting from traffic collisions. Uncertainties in collision forces were evaluated using peak dynamic forces published in research programs.

Silva et al. (2024) summarizes a reference list of experimental and numerical research projects that were conducted to evaluate peak dynamic forces resulting from traffic collisions. In total, 470 data points were obtained from the literature in assessing the variability of the Peak-DF for frontal collisions.

Figure 11 shows the general function for estimating uncertainties in the pulse loading function value, $\overline{F_{\mathrm{i}}}$. In this equation, *i* represents the Peak-DF in pulses 1, 2 and 3. These pulse functions are plotted in Figure 10.

$$\overline{F_i} = \overline{\gamma_{Fi,KE}} \left[\alpha_1 \, \overline{V_i}^{\beta_1} \alpha_2 \, \overline{W_i}^{\beta_2} \left(\frac{\overline{b_i}}{36} \right)^{\beta_3} \right]$$

Figure 11. Equation. General pulse function.

This general equation is evaluated using the random variables for the truck speed and weight, width of the bridge pier, and a loading factor $\overline{\gamma_{\mathrm{F}i,KE}}$. This loading factor was calculated as the ratio of reported versus calculated peak dynamic forces (Peak-DF). The calculated Peak-DF values were estimated using the pulse loading function using the reported truck speed and weight, and pier width.

Peak dynamic force $\overline{F_{\mathrm{i}}}$ (in kips) is evaluated separately at the three peak values: $\overline{F_1}$, $\overline{F_3}$, and $\overline{F_5}$. The loading factor $\overline{\gamma_{\mathrm{F}i,KE}}$ was also evaluated separately at these three peak values: $\overline{\gamma_{F1,KE}}$, $\overline{\gamma_{F3,KE}}$, and $\overline{\gamma_{F5,KE}}$. The loading factor, $\overline{\gamma_{Fi,KE}}$, was computed based on a random sampling using a best-fit curve.

Strain Rate effects on Material Properties

Strain rate effects on material properties for concrete and reinforcing steel were evaluated for impact loads resulting from vehicular collisions.

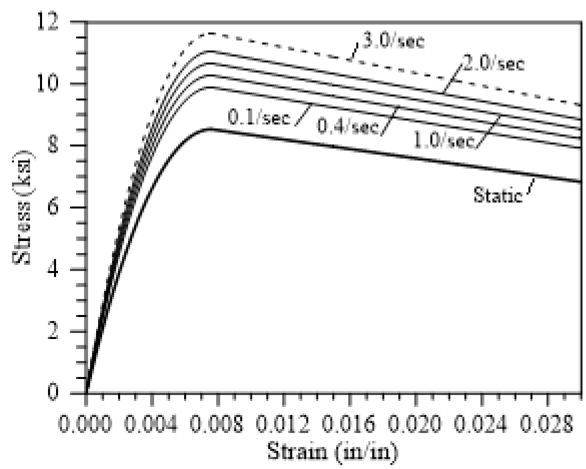
Concrete Properties

The CEB-FIP90 (1993) model was used to evaluate the concrete compressive strength for different strain rates. The dynamic increase factor (DIF) for the concrete compressive strength of confined and unconfined concrete were computed using Figure 12:

$$DIF = \left(\frac{\dot{\varepsilon_c}}{30 \times 10^{-6}} \right)^{1.026\left[1/\left(5+\frac{9f_c'}{1,450}\right)\right]}$$

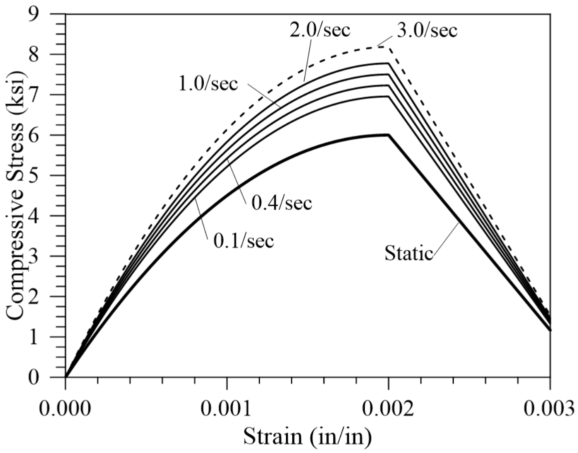
Figure 12. Equation. DIF for concrete compressive strength.

In Figure 12, $\dot{\varepsilon_c}$ is the strain rate for concrete in compression, and f_c' is the concrete compressive strength in psi. The effects of strain rate on the cyclic loading reversal of confined and unconfined concrete are presented, respectively, in Figure 13 and Figure 14.



Source: FHWA

Figure 13. Graph. Strain rates of confined concrete in compression.



Source: FHWA

Figure 14. Graph. Strain rates of unconfined concrete in compression.

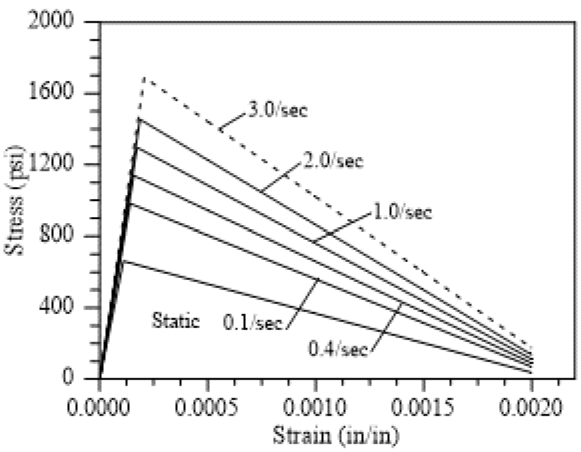
Likewise, The CEB-FIP90 (1993) model was used to evaluate the concrete tensile strength properties for different strain rates in terms of Figure 15.

$$DIF = \left(\frac{\dot{\varepsilon_c}}{30 \times 10^{-6}}\right)^{1.016\left[1/\left(10+\frac{6f_c'}{1,450}\right)\right]}$$

Figure 15. Equation. DIF for concrete tensile strength.

In Figure 15, $\dot{\varepsilon_c}$ is the strain rate for concrete in compression, and f_c' is the nominal design concrete compressive strength in psi.

Strain rates for the tensile strength of concrete are presented in Figure 16.



Source: FHWA

Figure 16. Graph. Strain rates of concrete in tension.

Reinforcing Steel Properties

The relations in Malvar's (1998) work were adopted in this study for the reinforcing steel. The DIF for the yield strength and ultimate strength of reinforcing steel are computed by Figure 17 and Figure 18, respectively.

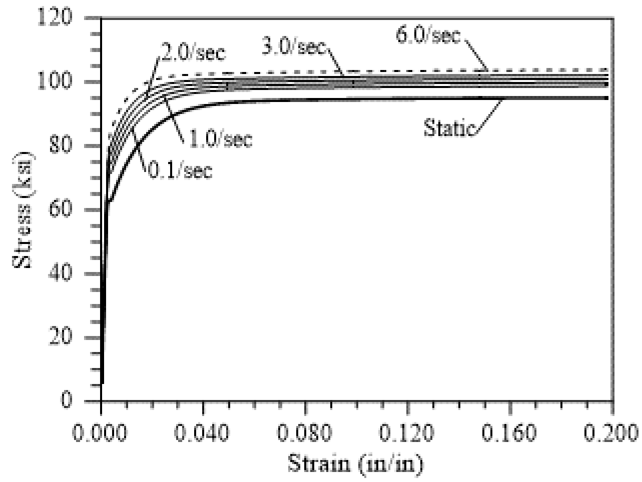
$$DIF_y = \left(\frac{\dot{\varepsilon_s}}{10^{-4}}\right)^{\left(0.074-0.040\frac{f_y}{60}\right)}$$

Figure 17. Equation. DIF for reinforcing steel yield strength.

$$DIF_u = \left(\frac{\dot{\varepsilon_s}}{10^{-4}}\right)^{\left(0.019-0.009\frac{f_y}{60}\right)}$$

Figure 18. Equation. DIF for reinforcing steel ultimate strength.

In these equations, $\dot{\varepsilon_s}$ is the strain rate effects for the reinforcing steel, and f_y is the nominal design yield strength in psi. Strain rate effects for the tensile strength of steel are presented in Figure 19.



Source: FHWA

Figure 19. Graph. Strain rates of reinforcing steel.

Stochasticity of System Parameters

Stochasticity of material properties design values, element level dimensions for reinforcing bar, members and bridge layout dimensions were established according to system parameters investigation carried by Mirza and MacGregor (1979).

Bridge system stochastic variables were also related to uncertainties in geometric dimensions and material properties. Following well established methodologies presented in Nowak and Collins (2012), uncertainties in system variables were developed considering their corresponding bias factor and coefficient of variation.

Summary and Conclusions

This report outlines a literature review of current state of design practice of bridges piers and girders against heavy truck collisions. This study includes experimental and analytical research on bridge failures resulting from these types of collisions, as well as stochastic models for evaluating the vulnerability of bridge piers and girders against heavy truck collisions.

Bridge inventory data, collision data, and traffic detector data from Virginia were analyzed to create a test bed study site consisting of 17 representative bridges. Results from the seventeen test bed study sites were used to characterize and validate these stochastic variables:

- Truck speed as a function of bridge location
- Truck weight as a function of bridge location
- Frequency of heavy truck collisions as a function of bridge location.
- Equivalent static forces resulting from frontal collisions.
- Strain rate effects from impact loads on material properties.
- Uncertainties in geometric dimensions and material properties.

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