Assessment of the MASH Heavy Vehicle Weights for Field Relevancy

Christine E. Carrigan, P.E., PhD
RoadSafe, LLC
Box 312
12 Main Street
Canton, Maine 04221
Phone: 207 513 6057, e-mail: christine@roadsafellc.com

Malcolm H. Ray, P.E., PhD
RoadSafe, LLC
Box 312
12 Main Street
Canton, Maine 04221
Phone: 207 514 5474, e-mail: mac@roadsafellc.com

Submitted
July 25, 2016

Resubmitted
October 31, 2016

Word count
Text = 4,530
Figures & Tables: 8 @ 250 words each =2,000
Total number of words= 6,530

Paper prepared for consideration of presentation and publication at the
96th Annual Meeting of the Transportation Research Board, January 2017

Assessment of MASH Heavy Vehicle Weights for Field Relevancy

Christine E. Carrigan and Malcolm H. Ray

ABSTRACT

Changes in vehicle fleet characteristics have prompted updates to crash testing specifications. This paper examined both the heavy vehicle types and weights in the traffic stream using a variety of available data sources to assess the relevance of the MASH with respect to field observations.

The 85th percentile single-unit truck was found to have a gross vehicle weight of 22,000 lbs indicating that the MASH 10000S SUT is, therefore, representative of the practical worst case single-unit truck.

The legal load limit in 35 States is 80,000 lbs. The Class 9 single-trailer truck has an 85th percentile GVW of about 77,000 lbs and the 99th percentile is just over 83,000 lbs. The MASH 36000V and 36000Tcrash test vehicles are 80,000 lbs Class 9 tractor trailer trucks so they represent the 95th percentile of Class 9 single-trailer truck weights and are a good choice for representing a broad range of tractor trailer trucks.

This review of observable data for traffic distributions and weight has shown that the MASH 10000S, 36000V and 36000T crash test vehicles appear to be appropriate choices for the performance evaluations of safety hardware and should continue to be used in that capacity. This review also showed considerable variation in the percentage of trucks by area type (i.e., urban and rural) and distribution of heavy vehicle types and loading within the percentage of trucks.

INTRODUCTION

The AASHTO Manual for Assessing Safety Hardware (MASH) contains recommendations for testing and evaluating the performance of safety hardware, including longitudinal barriers, terminals, crash cushions, work zone devices and breakaway structures. Changes in vehicle fleet characteristics were one of the reasons that prompted the initiation of NCHRP Project 22-14(02), "Improved Procedures for Safety-Performance Evaluation of Roadside Features" which in turn led to the development of MASH, published in 2009. *(1)* MASH includes essentially the same test level approach as NCHRP Report 350 with some changes to vehicle characteristics. The single unit truck (SUT) increased in weight and the c.g. height was raised. The weight of the tractor van-trailer and tractor tanker-trailer did not change between NCHRP Report 350 and MASH although the trailer length was increased. *(1, 2)*

This paper examined both the types and weights of heavy vehicles in the traffic stream using a variety of available data sources to assess the relevance of the MASH heavy vehicle characteristics to observable traffic conditions. Regional and national databases were queried to quantify the distribution of each type of heavy vehicle present within the over-arching “percent trucks” grouping. National survey data and regional weigh in motion (WIM) data were used to establish the weight distributions of each type of heavy vehicle and compare these distributions with the weights currently used in MASH when evaluating safety hardware for heavy vehicles.

HEAVY VEHICLE MIX

In the 1980’s FHWA developed a 13-vehicle classification system and asked the states to report data using these classifications when possible. *(3)* The classifications are based on configuration (i.e., single body, articulated tractor and trailer, etc.) and the number of axles. The FHWA requires each State Highway agency to conduct “continuous classification counters to measure truck travel patterns and provide the factors to convert short classification counts to annual averages.” *(3)* Figure 1 is a pictographic representation of each vehicle classification.*(4)*

Traffic engineers often characterize the traffic stream in terms of the percentage of each vehicle type in the traffic flow. The percentage of each type of vehicle in the traffic flow is called the traffic mix. The sum of the percentages of all the heavy vehicles in the mix is called the percent trucks (PT). The objective of this part of the study was to understand the distribution of heavy vehicle types within the PT. There are a variety of data sources which can be used to examine both the traffic mix and the distribution of heavy vehicles within the PT group.

NCHRP Report 505, “Review of Truck Characteristics as Factors in Roadway Design,” provides a review of the truck characteristics of the US truck fleet and also summarizes the general vehicle fleet characteristics. Recommendations for changes to highway geometric design policy to ensure that highway designs reasonably accommodate trucks were the ultimate objective of this study. *(5)* Harwood *et al.* found, using data from 1992 to 1997, five-axle tractor-trailer trucks (i.e., Class 9) alone account for 46.1 percent of the heavy vehicle miles traveled and two-axle single-unit trucks (i.e., Class 5) account for 29.5 percent. *(5)* After Class 5 and 9, the next highest class is represented by three-axle single-unit trucks (i.e., Class 7) at 5.3 percent. Class 5 (i.e., two-axle single-unit trucks) and Class 9 (i.e., five-axle tractor trailer trucks) together account for more than 75 percent of the heavy vehicle-miles travelled in the United States.

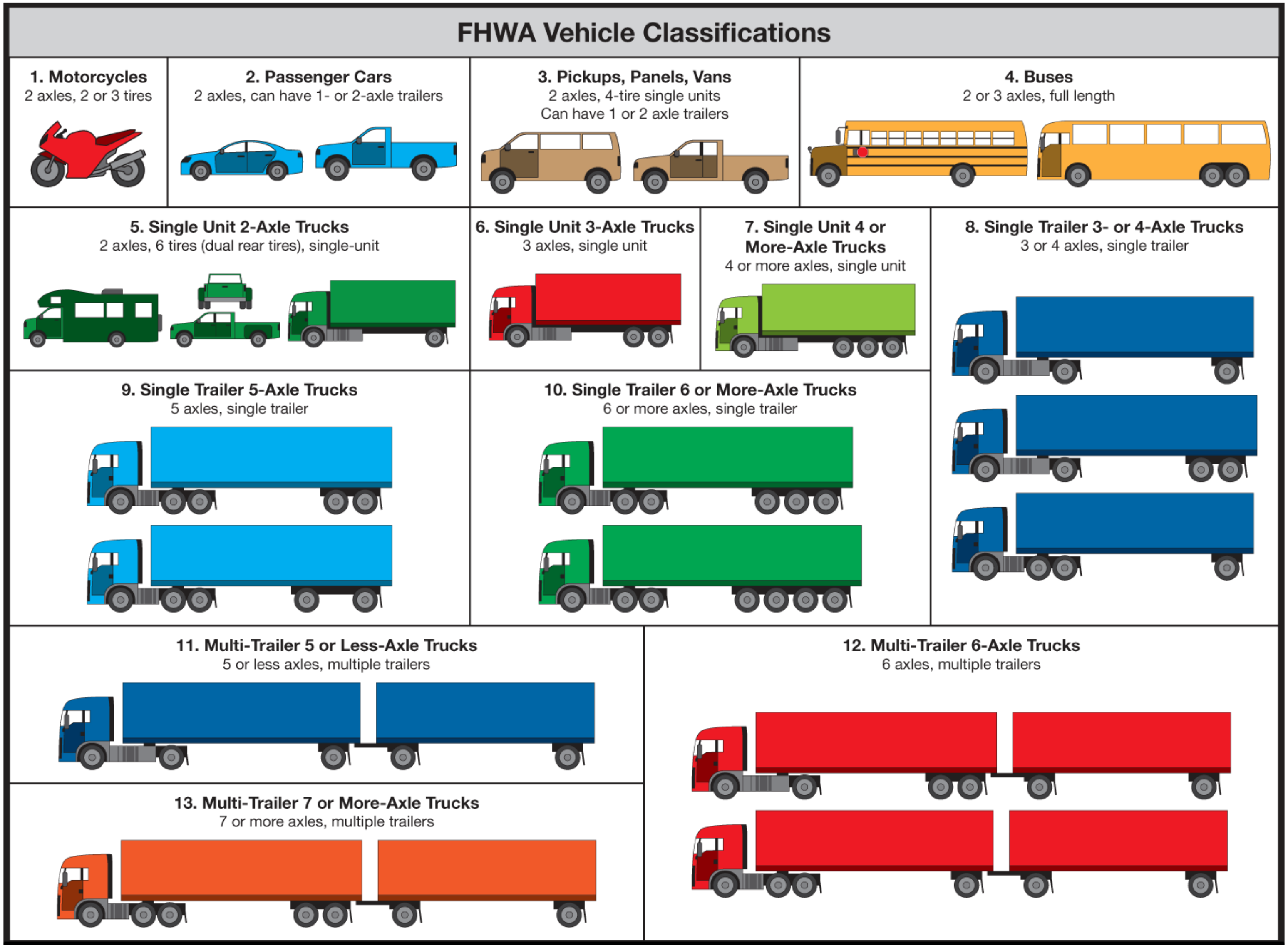

Figure 1 FHWA Vehicle Classifications *(4)*

FHWA Data

The FHWA annually publishes the "Highway Statistics Series" which includes reports of motor vehicle miles traveled by vehicle type and highway type. *(6)* The 2012 statistics have been compiled for both rural and urban areas and are referenced herein as "the FHWA data." Unfortunately, FHWA does not use its own vehicle classification system in the "Highway Statistics Series." Inferences were made for this paper. Specifically, where the "Highway Statistics Series" says motorcycles, it was presumed to equal FHWA class 1. Buses were presumed to equal FHWA class 4. Single Unit Trucks were presumed to equal FHWA classes 5-7 and Tractor-Trailer Trucks were presumed to equal FHWA Class 8-13.

Traffic mix data were also obtained from the states of New Jersey (NJ), Maryland (MD), Kansas (KS) and Washington (WA) and are included here as examples of the type of vehicle mix data commonly collected by the States. For example, the state of New Jersey publishes an annual traffic report where State-wide traffic volumes are summarized by the FHWA vehicle classification system. These data are broken into the complete 13-class FHWA system and typical Green Book roadway functional classifications. Recall the FHWA values are a distribution of vehicle miles traveled. The NJ, MD, and KS data are distributions of traffic volumes (i.e., point-in-time counts) which may vary by direction and are not normalized by the mileage of urban or rural roads in these states. The WA data is reported by vehicle-miles-traveled similar to the FHWA data.

The average values of PT for NJ, MD, WA, KS and nationally are shown in Figure 2 by area type (i.e., Urban and Rural) and functional classification of roadways. Notice that the PT is generally higher on both urban and rural interstates than other highway types.

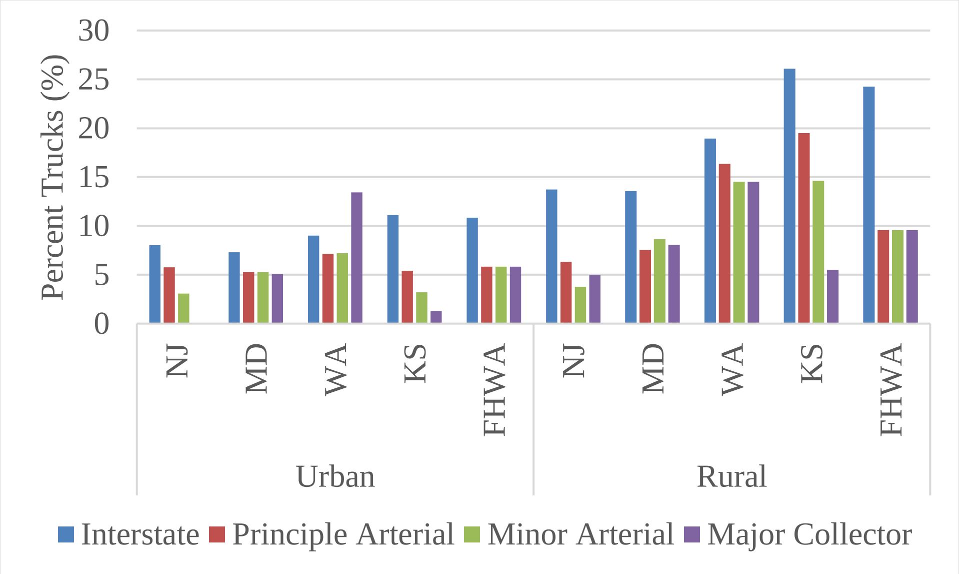

Figure 2 Variations in Average Percent Truck by Functional Class, Area Type, and State

There is considerable variation in the heavy vehicle fleet mix within the PT grouping as shown in the summary of the FHWA data provided in Table 1. There are generally five times more tractor trailer trucks (TT) on rural interstates than single unit trucks (i.e., 81.68/15.51=5.26) whereas there are about 30 percent more (i.e., 52.46/ 39.95=1.31) single-unit trucks (SUT) on urban off-interstate roadways than tractor trailer trucks. The type of roadway and land use, therefore, can have an effect on the heavy vehicle mix. This variation in mix can likely be attributed to the use of roadways for different purposes. Tractor-trailer trucks hauling goods over large distances will prefer Interstate and other principal arterials. In urban areas, the mix is dominated more by local delivery vehicles and regional movement of goods typical of single-unit delivery trucks. Similarly, buses are twice as common in the heavy vehicle mix on local urban routes as on rural interstates due to the nature of the trips being generated.

Table 1 FHWA 2012 Distribution of Heavy Vehicle-Miles Traveled by Heavy Vehicle Type

Vehicle Type	RURAL			URBAN			Total Rural and Urban (%)
	Interstate (%)	Other (%)	All (%)	Interstate (%)	Other (%)	All (%)	
Buses	2.81	5.92	4.02	4.49	7.59	6.43	5.21
SUT	15.51	52.35	31.09	27.69	52.46	43.18	37.08
TT	81.68	41.73	64.89	67.82	39.95	50.39	57.71

State Data

The 2012 heavy vehicle distributions by highway functional classification for the states of New Jersey, Maryland, and Kansas are shown in Figure 3. *(7, 8, 9)* This figure is a distribution of the different classes of heavy vehicles (e.g., bus, SUT, TT) within the heavy vehicle group, which is to say that the distribution sums to 100 percent for heavy vehicles. Passenger vehicles are excluded.

Figure 2 shows that in New Jersey the highest percent of trucks occurs on the rural interstates (i.e., 13.73 percent) and the lowest on the urban minor arterials (i.e., 3.07 percent). The mix within the heavy vehicle fleet, as shown in Figure 3, shows buses (color blue on graph) account for between about 1 and 5 percent of the heavy vehicles with somewhat higher percentages on the urban roads. Single-trailer trucks (i.e., class 8-10) account for almost 80 percent of the rural interstate heavy vehicle traffic in New Jersey whereas SUTs dominate the urban principal arterials.

The New Jersey, Kansas and Maryland distributions are based on traffic volumes whereas the Washington distribution is based on vehicle miles traveled as is the FHWA data shown earlier. The Washington data is summarized in Figure 4. The highest percent of trucks in these four States occurs on the rural interstates and varies between a high of 26 percent in Kansas and a low of just over 13 percent in New Jersey and Maryland. The lowest percent trucks in all four States occur on the urban arterials varying between three and six percent.

Tractor trailers account for between 70 and 80 percent of the heavy vehicle volume on rural principal arterials whereas single-unit trucks are more prevalent on lower functional class roads. Multi-trailer trucks accounted for about 10 percent of the heavy vehicle volume in the two western States whereas the multi-trailer truck volume in the two eastern States was around 5 percent on the principal arterials and interstates. Aside from the principal arterials, there are relatively few multi-trailer trucks travelling on other functional classification roadways. The same pattern of larger tractor trailer proportions of the heavy vehicle mix on the rural interstate system to the urban system holds in each State shown. Similarly, the mix of tractor trailer and single-unit trucks reverses on more locally oriented functional classification roadways.

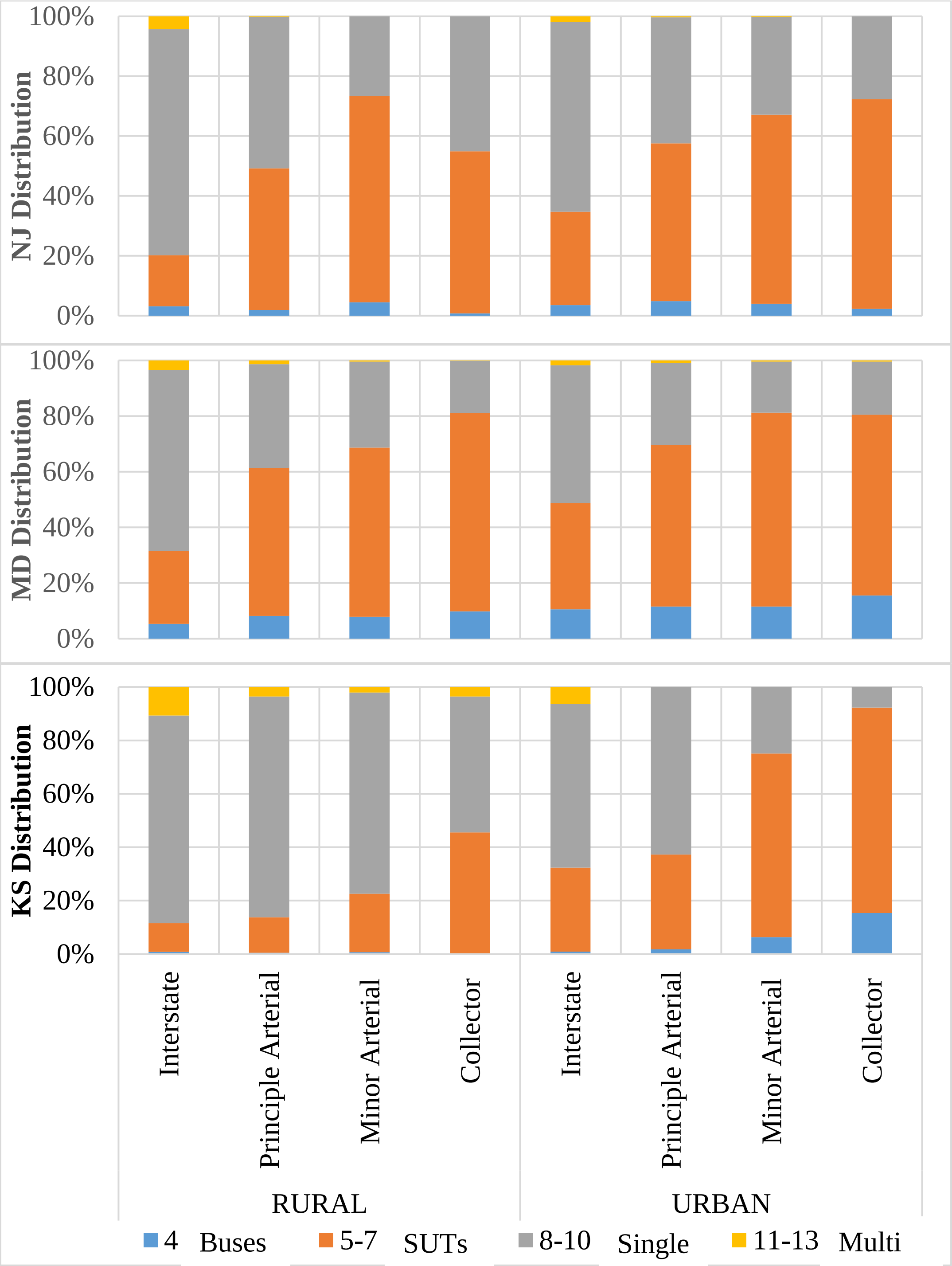

Figure 3 Distribution of Heavy Vehicle Type within PT by Highway Type

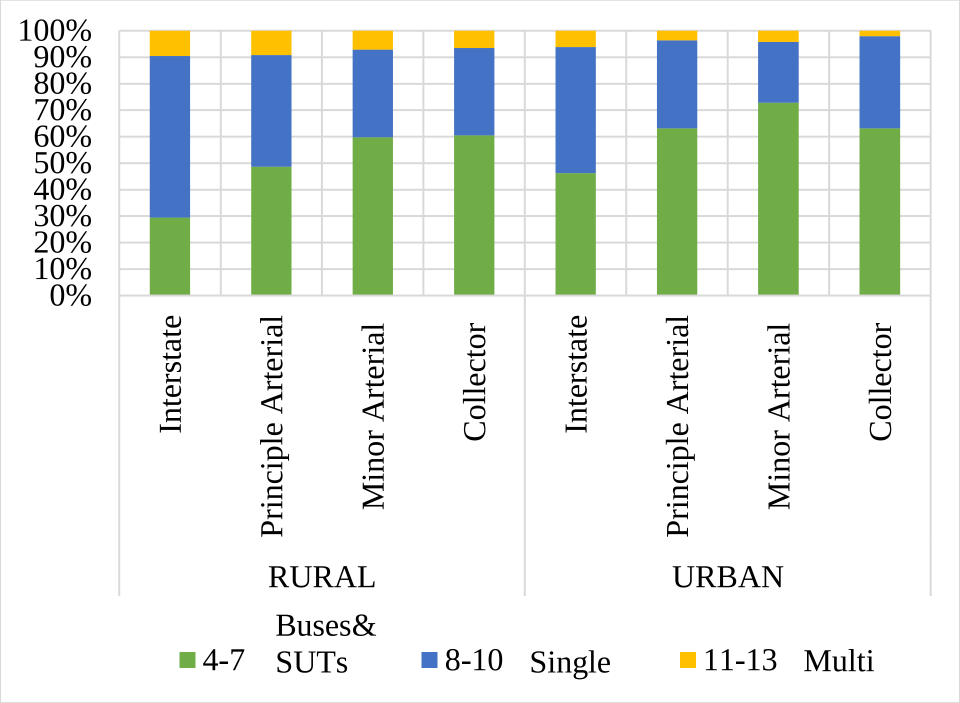

Figure 4 Washington Distribution of Heavy Vehicle Type within PT by Highway Type

Summary

The heavy vehicle mix appears to be most strongly affected by the land use (i.e., rural versus urban) and whether the roadway is an arterial or a collector. All the State mix data examined showed that single-trailer trucks generally account for about 70 percent of the truck volume on rural interstate roadways. Multi-trailer trucks also account for a small percentage (i.e., around 5 percent) on rural interstates. The tractor trailer classes (i.e., Classes 8 through 13) often account for 75 percent of the rural arterial and interstate truck volume. The tractor trailer truck percentage decreases somewhat on urban arterials while single-unit trucks increase as the functional class becomes more local and urban.

The Class 5 SUT and Class 9 TT trucks appear most frequently in the fleet across all roadway classifications and areas types (i.e., urban or rural) and generally account for 75 percent of the heavy vehicle-miles travelled. Class 5 SUTs and Class 9 TT are, therefore, the most common heavy vehicle body styles and axle configurations. The continued use of the Class 5 SUT and Class 9 TT the crash testing of hardware is supported by these heavy vehicle mix data. The crash test evaluation of hardware using these two very common heavy vehicle body styles/axle configurations appears to be appropriate given that the underlying philosophy of crash testing is to evaluate the practical worst case impact scenario.

Consideration should be given to the national variations in both percent trucks and the distribution of heavy vehicles within the percentage of trucks when developing hardware test level selection guidance for incorporation in the Roadside Design Guide. The following section assesses the appropriate weights of these vehicles for testing purposes.

HEAVY VEHICLE PROPERTIES

Knowing the distribution of the most common types of heavy vehicles is the first step; the second step is to determine the appropriate gross vehicle weight (GVW) of the predominant heavy vehicles in order to evaluate if the MASH test vehicles are a reasonable representation of practical worst case field conditions. Weight is a particularly important property for roadside design since the vehicle weight is one of the two basic components of kinetic energy.

Gross Vehicle Weight Limits

Each State imposes a maximum gross vehicle weight (GVW) for their highways. A vehicle can only be loaded above this weight if it is specially permitted. As shown in Table 2, 35 States have a maximum GVW of 80,000 lbs. Alaska has the highest limit at 150,000 lbs, Montana and Nevada have limits of 129,000 lbs and six States have limits between 95,000 and 105,000 lbs. Vehicles with weights above the legal limit can be specially permitted, but the legal limit is an indicator of the highest loads that can normally be expected.

Table 2 Maximum Legal Load by State

Maximum Unpermitted Legal Load (x 1,000 lbs)												
150	132	129	105	100	95	90	88	86.4	85.5	85	80.608	80
States												
AL	MT	NV	ID ND OR WS	ME	NE	OK	HI	NM	KS	CO	SC	All Others

Distribution of Vehicle Weights

Heavy vehicle weights were assessed by examining five different databases: (1) the Vehicle Travel Information System (VTIS), (2) the NAS heavy vehicle fuel consumption study, (3) the FHWA Vehicle Inventory and Use Survey (VIUS), (4) the Mechanistic-Empirical Pavement Design Guide (MEPDG) and (5) NCHRP Report 683 WIM data. These data are briefly discussed below.

The FHWA Office of Highway Policy Information (OHPI) publishes the Vehicle Travel Information System (VTIS) website which can be queried for data on the average time heavy vehicles spend both empty and loaded. VTIS data from Nevada for the year 2013 was evaluated to determine the 50th percentile weight of heavy vehicles on urban and rural roadways. *(10)* Recall from above that Nevada has a maximum gross vehicle weight limit of 129,000 lbs.

The National Academy of Sciences and FHWA published “Technologies and Approaches to Reducing the Fuel Consumption of Medium and Heavy-Duty Vehicles” in 2010.*(11)* Data from 2008 were gathered and analyzed from the following 15 States: California, Connecticut, Florida, Georgia, Hawaii, Iowa, Minnesota, Missouri, Montana, North Carolina, Oregon, Pennsylvania, South Dakota, Texas, and Washington. The analysis includes the consideration of on-road vehicle weight for five-axle tractor-trailer trucks (i.e., Class 9). Using the data presented in that report, a cumulative distribution of GVW was generated for Class 9 vehicles. The summary statistics for the Class 9 weight distribution were extracted to determine that the median Class 9 vehicle has a GVW of about 53,000 lbs and the 99th percentile Class 9 vehicle weighs just over 90,000 lbs.

The FHWA Vehicle Inventory and Use Survey (VIUS) data from 2002 was evaluated to determine the GVW of different vehicle classes. *(12)* The data provides the physical and operating characteristics of the heavy vehicle population for each State. The data is gathered through surveys, not field measurements. The average payload and empty weights were calculated from the survey data and used to generate a national average distribution for each heavy vehicle class. Since the VIUS is a trucking company survey, Class 4 vehicles (i.e., buses) were not included in the data. Unfortunately, the VIUS data is reported using a different vehicle classification system than the FHWA classification system, therefore, an equivalency table was developed.*(13)* For example, the VIUS Single Unit:2-axle was determined to be equivalent to the FHWA class 5. The VIUS Single Unit: 3-axle was determined to be equivalent to the FHWA class 6. The VIUS Single Unit 4-axle or more was determine to be equal to the FHWA class 7. The VIUS truck/tractor trailer 4-axle, 5 axles, and 6 axle were determine to be equivalent to the FHWA class 8, 9, and 10 respectively.

A cumulative distribution of tandem-axle weights for each of the heavy vehicle classes from the Mechanistic-Empirical Pavement Design Guide (MEPDG) *(14)* was developed. The MEPDG does not list the distributions of vehicle weights but only the distribution of axle weights. The MEPDG data were used to estimate the GVW distribution by combining the single and tandem axle distributions according to the number and axle configuration for each of the heavy vehicle types in the FHWA classification system.

Many states maintain weigh-in-motion (WIM) data collection stations to collect the axle loadings of heavy vehicles in order to assist in pavement designs. WIM data were obtained from NCHRP Project 12-76(01) which is documented in NCHRP Report 683, “Protocols for Collecting and Using Traffic Data in Bridge Design.” *(15)* Two specific WIM stations were selected for study here because data was available for at least 10 months of the year and included all lanes of the cross-section. The first WIM station is WIM site number 1 in Lodi, California. The data were collected for 10 months between June 2006 and March 2007. The second WIM station is WIM site number 9919 in Brevard County, Florida. The data were collected for the 12 months of 2005.

The results from each of these five datasets are summarized in Figure 5 and Figure 6. While all the data is fairly similar it is certainly not identical. Each different data source includes its own assumptions and definitions such that there are nuances between all the different data sources. Figure 5 summarizes all SUT data and Figure 6 summarizes all the TT data. In these figures, each marker style represents a different percentile of the GVW distribution for that vehicle class and the box indicates the range between the 50th and 99th percentile.

The MEPDG data generally shows the widest range (i.e., lowest average and highest 99th percentile) which is due to the way the data had to be re-aggregated to estimate the GVW. Since only axle weight distributions were provided an assumption about how to combine them had to be made. The assumption was that the appropriate single and tandem axles would come from the same percentile in the distribution presuming the trucking companies attempted to balance their loads. This certainly would not always be the case so it should be recognized that the 50th percentile of the MEPDG is probably on the low side while the 99th percentile is probably over-estimated. At the other extreme are the VTIS and VIUS data which are compiled from surveys of trucking companies rather than direct measurements. Based on a careful examination of the data it is highly likely that loads are sometimes incorrectly reported and there is likely often confusion among the survey takers about the loaded and unloaded configurations. As a result, the VIUS and VTIS data tend to have higher mean values and lower 99th percentiles. The WIM data is a highly accurate measurement of the GVW of each vehicle passing since it is explicitly measured but it only represents those two particular highways sections rather than a national distribution. Each data source, then, has certain inherent advantages and disadvantages such that there is no single absolutely correct distribution. A reasonable value that is consistent with each of these five databases while not necessarily exactly matching them would be representative of the heavy vehicle fleet and an appropriate MASH test vehicle weight. In general, the WIM data was preferred since it is an actual measure of specific vehicles.

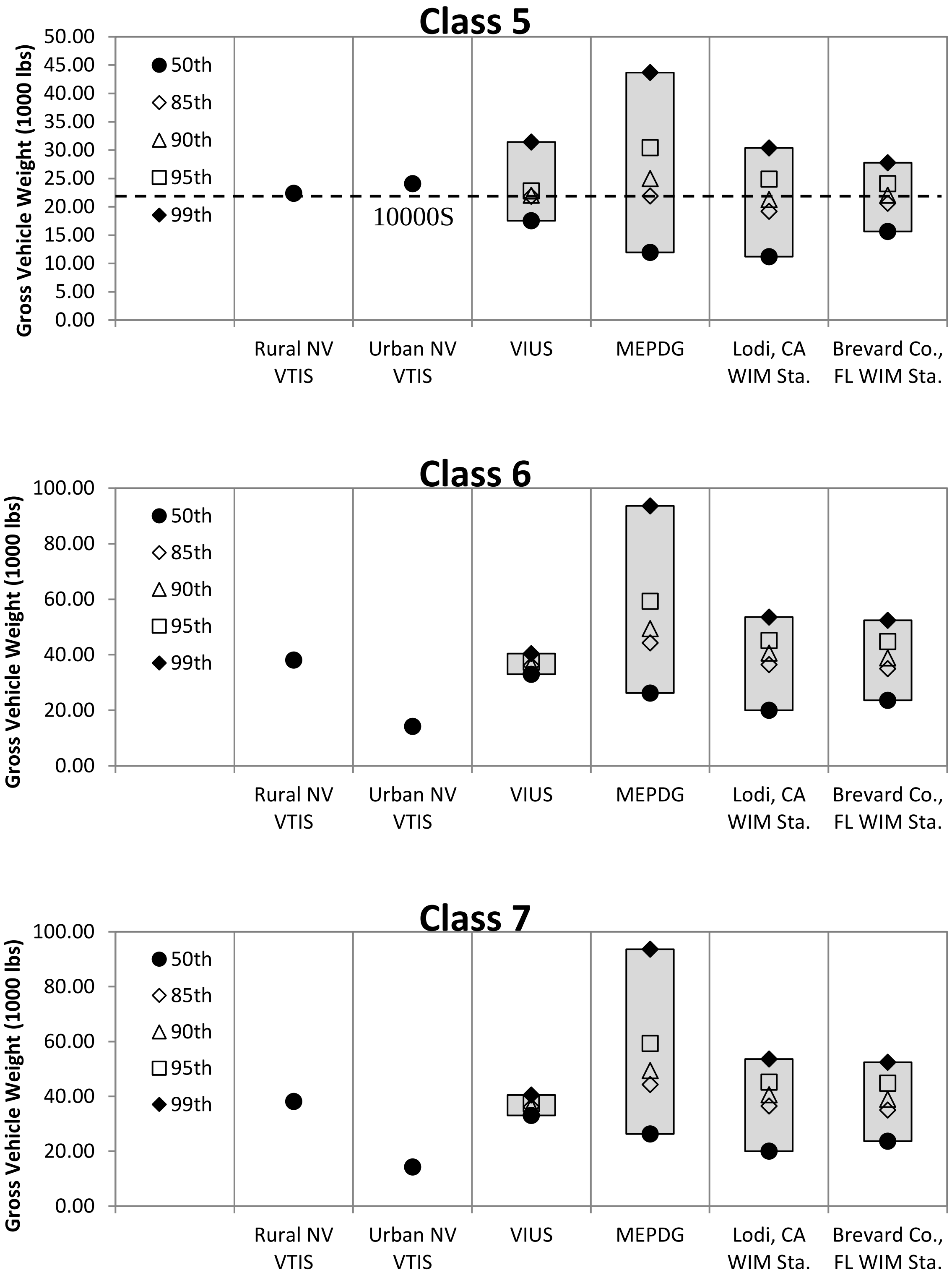

Figure 5 Comparison of SUT GVWs from all data sources

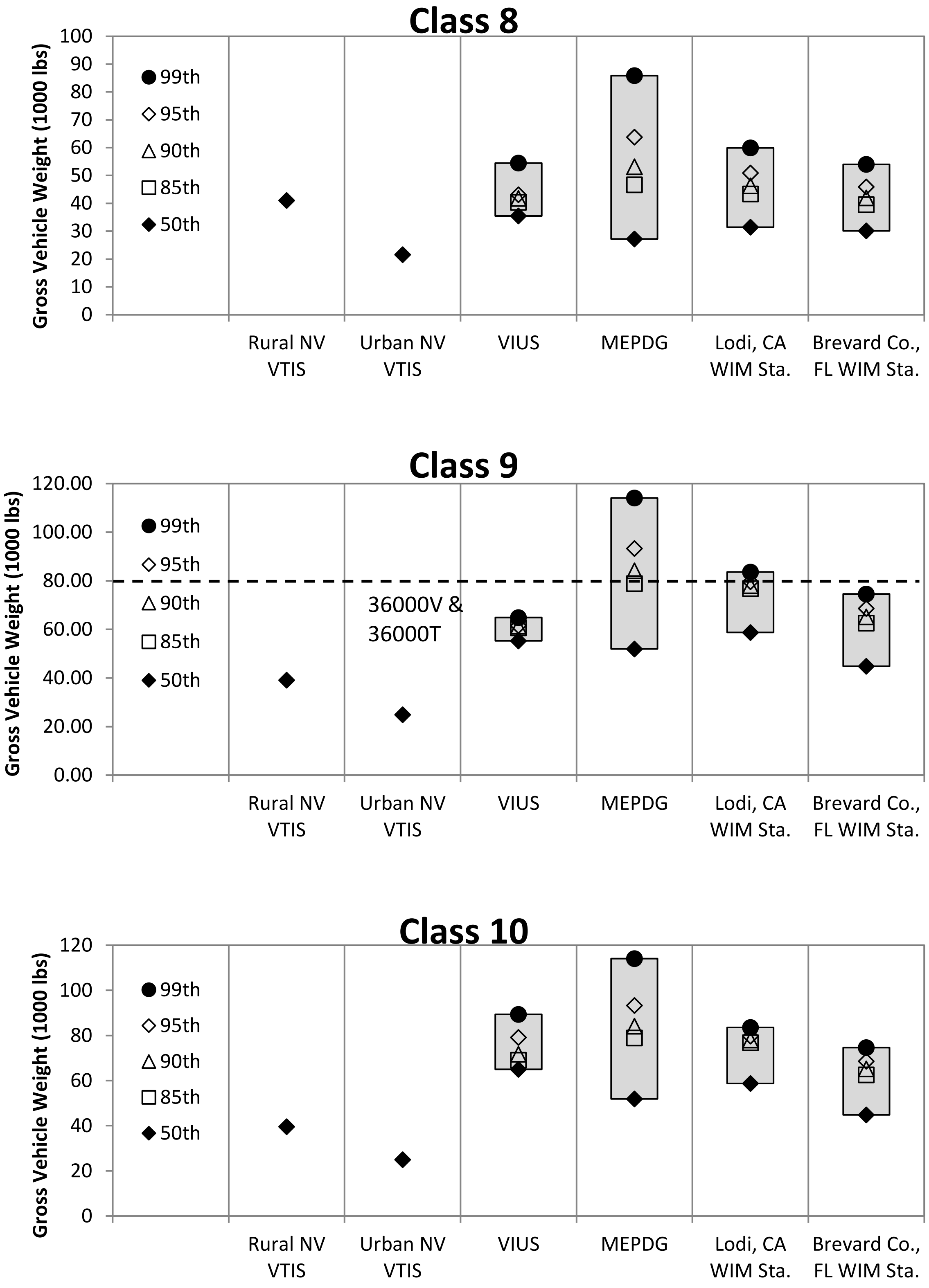

Figure 6 Comparison of Truck-Trailer GVWs from all data sources

RESULTS AND CONCLUSION

Buses (i.e., Class 4) were shown to account for between 5 and 10 percent of the heavy vehicle traffic depending on the functional classification of the roadway. The WIM data indicates that even the heaviest buses weigh less than 60,000 lbs and the mean is about 30,000 lbs so buses always have a smaller weight that the test level 5 or 6 MASH test vehicles. Crash test recommendations have long presumed that the reasonable extremes of body styles can be used as surrogates for other styles. Not including buses (Class 4) in the MASH recommended test matrix appears reasonable because they are underrepresented in the data and have a measurably lower weight than other heavy vehicles. In other words, MASH appears to presume that the heavier test level 5 vehicles are a suitable surrogate for buses.

The SUT classes (i.e., Classes 5-7) summarized earlier in Figure 5 represent the most varied group of heavy vehicles with many different body styles, configurations and uses. Class 5 SUTs can be difficult to distinguish from a heavy Class 3 dual-rear wheel pickup truck with vehicle counting equipment but, as shown earlier, Class 5 SUTs account for nearly 30 percent of the heavy vehicle miles travelled. The SUT used in Report 350 and MASH crash tests is a Class 5 vehicle. Classes 6 and 7 are very similar to Class 5 except they use tandem and triple axles in the rear. If all SUTs (i.e., Classes 5 through 7) are grouped together, the 50th percentile GVW is around 15,000 lbs, the 85th around 22,000 lbs and the 99th about 50,000 lbs. The 85th percentile SUT at 22,000 lbs is a reasonable choice for the MASH 10000S SUT vehicle used in test level four crash tests since it is representative of field observations. The MASH 10000S SUT appears to be a reasonable surrogate for Class 5 through 7 SUTs since the Class 5 body style and axle configuration is the most common and the 22,000-lbs weight is the 85th percentile for the entire group.

The tractor, singletrailer classes (i.e., Classes 8-10) are all articulated heavy vehicles that only differ in the number of axles at the king-pin or the rear of the trailer. The average Class 9 single-trailer truck has a GVW of about 59,000 lbs, the 85th percentile is about 77,000 lbs and the 99th percentile is just over 83,000 lbs. Multi-trailer trucks (i.e., Classes 11-13) are either not allowed or only allowed by special permit in many States and, therefore, account for only a small proportion of the heavy vehicle mix. MASH, like Report 350 before it, includes two tractor trailer truck vehicles; the 36000V van-type tractor trailer truck and the 36000T tanker-trailer truck. While both weigh 80,000 lbs, the first uses a van-type trailer whereas the later uses a stiffer, tanker trailer. Both, however, are Class 9 TTs. The vehicle weight data described in the previous section could not distinguish between the two types of trailers. As shown in the first section, the Class 9 configuration is by far the most common TT configuration found on the nation's highways and, therefore, it appears to be a reasonable surrogate for the whole tractor trailer truck group (i.e., Classes 8 through13).

The MASH 36000V and 36000T crash test vehicles are 80,000 lbs Class 9 tractor trailer so they represent trucks at about the 95th percentile of Class 9 single-trailer truck GVWs. The legal load limit in 35 States is also 80,000 lbs so a 95th percentile tractor trailer truck weighing 80,000 lbs is also a good surrogate for representing the upper end of the weight distribution for the entire group of Class 8 through 13.

This review of observable data for traffic distributions and weights has shown that the MASH 10000S, 36000V and 36000Tare appropriate choices for the performance evaluation of safety hardware in MASH.

This review also showed considerable variation in the percentage of heavy vehicle types by area type (i.e., urban and rural) and highway functional classification. It is recommended that future guidance developed for the selection of the appropriate test level for safety hardware in the Roadside Design Guide explicitly allow for the vehicle mix to be varied in the selection criteria.

ACKNOWLEDGEMENTS

This paper was based on work performed as part of National Cooperative Highway Research Program (NCHRP) Project 12-90, “Guidelines for Shielding Bridge Piers.” The authors would like to thank the NCHRP for its support and the NCHRP project staff and the project panel for their comments, suggestions and direction.

REFERENCES

1 Technical Committee for Roadside Safety, “Manual for Assessing Safety Hardware,” American Association of State Highway and Transportation Officials, Washington, D.C., 2009.
2 H. E. Ross, Jr., D. L. Sicking, R. A. Zimmer and J.D. Michie, “Recommended Procedures for the Safety Performance Evaluation of Highway Features,” Report 350, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C., 1993.
3 Federal Highway Administration, “Traffic Monitoring Guide”, online version http://www.fhwa.dot.gov/ohim/tmguide/tmg4.htm#_ftn3, accessed September 29, 2010, May 1, 2001
4 Texas Department of Transportation, “Traffic Recorder Instruction” Manual http://onlinemanuals.txdot.gov/txdotmanuals/tri/classifying_vehicles.htm, dated February 01, 2012 online version access March 10, 2014.
5 Harwood, D.W., Torbic, D.J., Richard K.R., Glauz, W.D., Elefteriadou, L., “Review of Truck Characteristics as Factors in Roadway Design,” National Cooperative Highway Research Program Report 505, Transportation Research Board, Washington, D.C., 2003.
6 Federal Highway Administration, “Highway Statistics Series,” access online, March 11, 2014, Main access page, http://www.fhwa.dot.gov/policyinformation/statistics.cfm.
7 New Jersey Department of Transportation, “Roadway Information and Traffic Monitoring System Program,” Vehicle Classification, http://www.state.nj.us/transportation/refdata/roadway/pdf/TravelActivityVehTypeByRegion.pdf, Accesses online March 10, 2014.
8 State Highway Administration of Maryland, “Percent Of Vehicle Classifications By Functional Class For The Year 2014” http://www.roads.maryland.gov/oppen/Vehicle_Class.pdf, accessed online March 10, 2014
9 Kansas Department of Transportation, “KDOT Vehicle Classification Surveys,” accessed online https://www.ksdot.org/burtransplan/prodinfo/VehicleClass.asp, March, 2014.

10 Federal Highway Administration, "VTRIS W-Table web site," https://fhwaapps.fhwa.dot.gov/vtris-wp/about.aspx, accessed March 10, 2014.

11 National Academy of Sciences, "Technologies and Approaches to Reducing the Fuel Consumption of Medium and Heavy-Duty Vehicles," 2010.

12 Alam, M., Rajamanickam, G., "Development of Truck Payload Equivalent Factor (TPEF)," Office of Freight Management and Operations, Federal Highway Administration, June 15, 2007, Modified December 3, 2013, accessed online http://ops.fhwa.dot.gov/freight/freight_analysis/faf/faf2_reports/reports9/index.htm#toc, March, 2014.

13 Ray, M.H., Carrigan, C.E., Plaxico, C.A., "Guidelines for Shielding Bridge Piers," NCHRP Project 12-90, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C., (in progress).

14 ARA, "Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures," National Cooperative Highway Research Program Project 1-37A, Transportation Research Board, Washington, D.C., March 2004. http://onlinepubs.trb.org/onlinepubs/archive/mepdg/guide.htm

15 Sivakumar, B, M. Ghosn and F. Moses, "Protocols for Collecting and Using Traffic Data in Bridge Design," NCHRP Report 683, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C., 2011.