BRIDGES OVERLOADED BY HEAVY VEHICLES

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Abstract: The knowledge of the actual live load is important for a rational management of highway bridges. The forms of damage due to live load include fatigue cracking, formation of pot-holes, excessive vibration and deflection and in extreme cases even a catastrophic collapse. It has been observed that traffic load is strongly site-specific. There are considerable differences in traffic volume and weight of trucks. Recently, a substantial data base has been collected using Weigh-in-Motion (WIM) stations. The objective of this paper is to review the available WIM data and assess the degree damage in highway bridges depending on traffic volume (ADTT) and weight of heavy vehicles. The cumulative distribution function (CDF) of the gross vehicle weight (GVW) is considered separately for different types of vehicles. The live load effects are calculated using influence lines of moments and shear forces for a wide range of span length. The results are plotted on the probability paper for an easier interpretation of the results. For the considered locations, the percentage of overloaded vehicles is determined to facilitate a site-specific comparison. The present study confirmed that for each WIM location, it is possible to pin-point which types of vehicles have a major contribution to bridge damage.

Keywords: weigh-in-motion, bridge live load, fatigue loads, statistical parameters, gross vehicle weight, vehicle class.

1. Introduction

Transportation structures such as roads and bridges are exposed to moving traffic loads. Excessive static and dynamic live load effects can cause damage or even collapse of structural components or whole structures. To prevent failures, it is important to provide an adequate safety margin in the design, i.e. load effects are overestimated and load carrying capacity (resistance) is underestimated. In the new generation of design codes, safety reserve is provided in terms of load and resistance factors that are determined in the reliability-based calibration process (Nowak and Collins 2013). The acceptance criterion is closeness to the target reliability index. The code calibration requires the knowledge of statistical parameters of load and resistance, in particular, this applies to live load. It is important to know the cumulative distribution of live load for the considered location (road or bridge) and predict what is the maximum live load that can be expected within a given time period, e.g. a day, a week, a month, a year, and so on. The objective of this paper is to present the development of live load statistics using the weigh-in-motion (WIM) data from several locations in Alabama.

The WIM data includes gross vehicle weight (GVW), vehicle type, axle spacing, axle loads, time of record and also vehicle speed. To calculate the load effects such as moment and shear force, the vehicles from the WIM database are "run" over influence lines. The resulting load spectra are presented in form of cumulative distribution functions (CDF) on the normal probability paper. CDF's plotted on the normal probability paper allow for an easier interprettation of the results. If the resulting CDF is in form of a straight line, the corresponding GVW, moment or shear can be considered as a normal random variable. The mean value and standard deviation can be read directly from the graph. Information on construction and interpretation of the normal probability paper can be found in the probability textbooks, e.g. Nowak and Collins (2013).

2. WIM data base

The considered WIM data base includes over 35 million vehicles, collected by the Alabama Department of Transportation (ALDOT) in 13 locations in the State of Alabama. For each location the records include at least one year of data, in some locations even from 2009 to 2014. Significant site-specific differences were observed, so the WIM data was processed separately for each location. Special MATLAB routines were developed to convert the data into the required format. A summary of all the available records is presented in Table 1 for each location identified with a station code and year.

Table 1. Number of vehicles in the WIM data base for years 2009–2014

Station code	Name	2009	2010	2011	2012	2013	2014	Total
911	Alex City	–	–	–	–	353,633	538,856	892,489
915	Sunlower	–	345,597	615,175	75,275	290,776	266,977	1,593,800
918	Buckswille	–	–	–	–	–	–	–
931	Athens	2,384,627	2,709,822	2,694,092	–	–	1,380,492	9,169,033
933	Muscle Shoals	1,350,769	1,548,100	1,597,679		630,507	381,962	5,509,017
934		–	–	–	–	210,097	211,150	421,247
942	Pine Level	–	–	–	–	691,034	463,708	1,154,742
960	Whatley	–	–	–	–	328,867	214,014	542,881
961		–	–	–	–	1,332,267	976,565	2,308,832
963	Grand Bay	–	–	–	–	2,981,883	2,180,963	5,162,846
964	Ozark	988,972	1,242,340	1,178,145	–	600,608	485,182	4,495,247
965	Shorter	–	–	–	–	106,269	1,536,511	1,642,780
	US 231	–	–	–	197,500	1,264,143	588,025	2,049,668

However, the records include all the vehicles, also motorcycles, cars and light trucks that do not cause any damage to bridges. It was observed that some data points were recorded incorrectly. For location denoted as US 231, in addition to weights and geometry, the vehicles were photographed and the pictures were also recorded. The confrontation of photographs with other recorded information was very helpful in identifying of the false data. Therefore, the available WIM data was filtered to remove light-weight vehicles and questionable records. Additional filtering criteria were developed to identify heavy vehicles that can cause significant damage to road and bridges (Fig. 1). A summary of the WIM database after the filtering is shown in Table 2.

Table 2. Number of vehicles in ALDOT WIM data left after filtering procedure

Station code	Name	2009	2010	2011	2012	2013	2014	Total
911	Alex City	–	–	–	–	228,881	207,849	436,700
915	Sunlower	–	132,753	254,395	33,244	182,757	163,316	766,465
918	Buckswille	–	–	–	–	–	–	–
931	Athens	1,504,020	1,615,696	1,551,436	–	–	937,245	5,608,397
933	Muscle Shoals	757,286	815,636	609,927	–	407,645	247,560	2,838,054
934		–	–	–	–	100,471	100,058	200,529
942	Pine Level	–	–	–	–	518,677	350,063	868,740
960	Whatley	–	–	–	–	249,729	166,130	415,859
961		–	–	–	–	778,213	434,096	1,212,309
963	Grand Bay	–	–	–	–	512,083	341,269	853,352
964	Ozark	532,470	669,615	613,820	–	398,868	328,511	2,543,284
965	Shorter	–	–	–	–	75,402	1,150,834	1,226,236
	US 231	–	–	–	41,153	280,680	130,743	452,576
							TOTAL	17,422,531

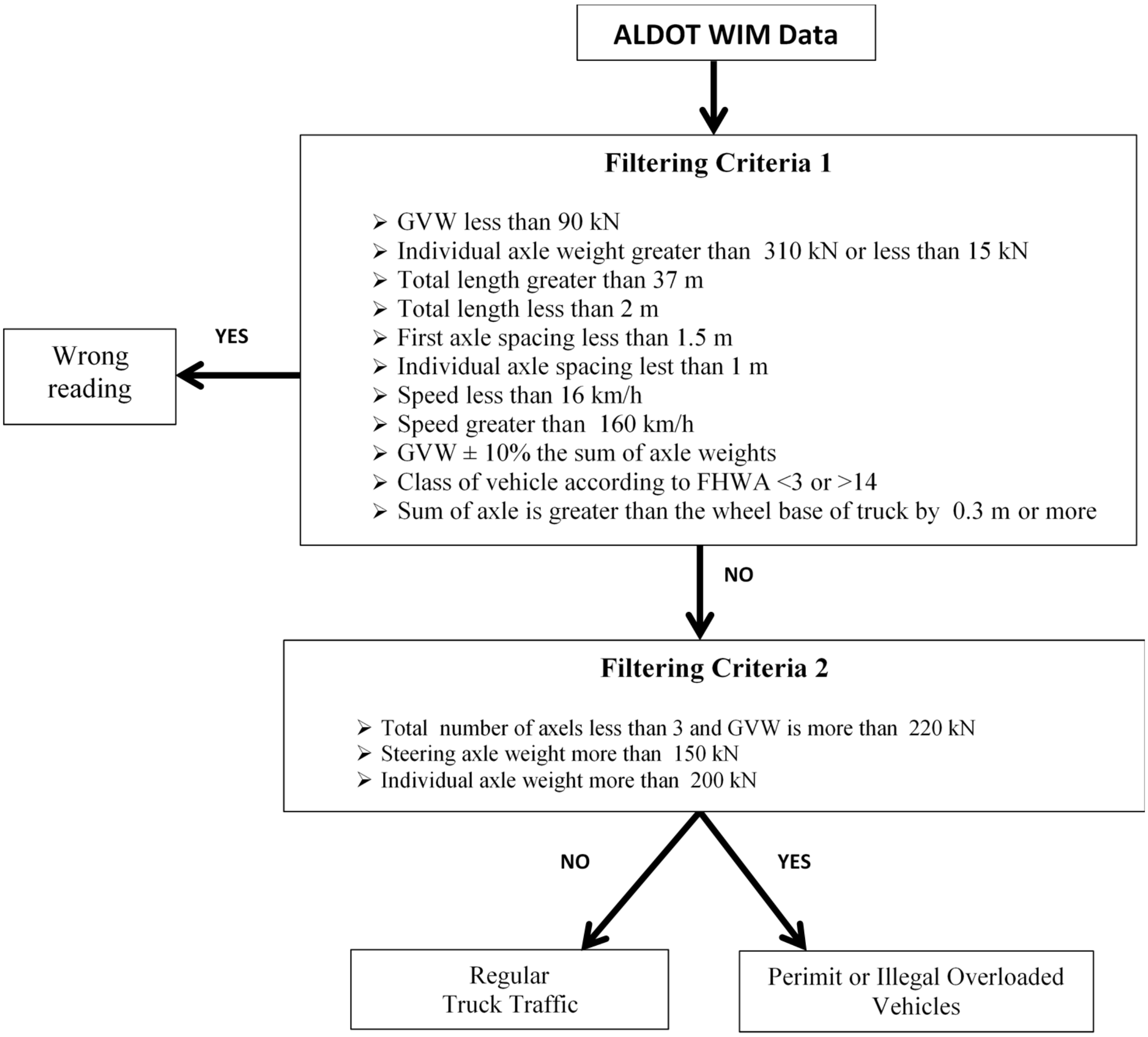

Figure 1: Filtering criteria

3. Gross vehicle weight (GVW)

The gross vehicle weight (GVW) was considered for each location and year. For example, the frequency histogram of GVW for location US231 and year 2014 is plotted in Fig. 2. The cumulative distribution functions (CDF's) of GVW is shown in Fig. 3. However, for an easier interpretation of the results, the CDF of GVW is plotted on the normal probability paper in Fig. 4. From the latter graph it is clear that 2% of all vehicles have GVW larger than 350 kN, and only 0.1% exceeds 450 kN.

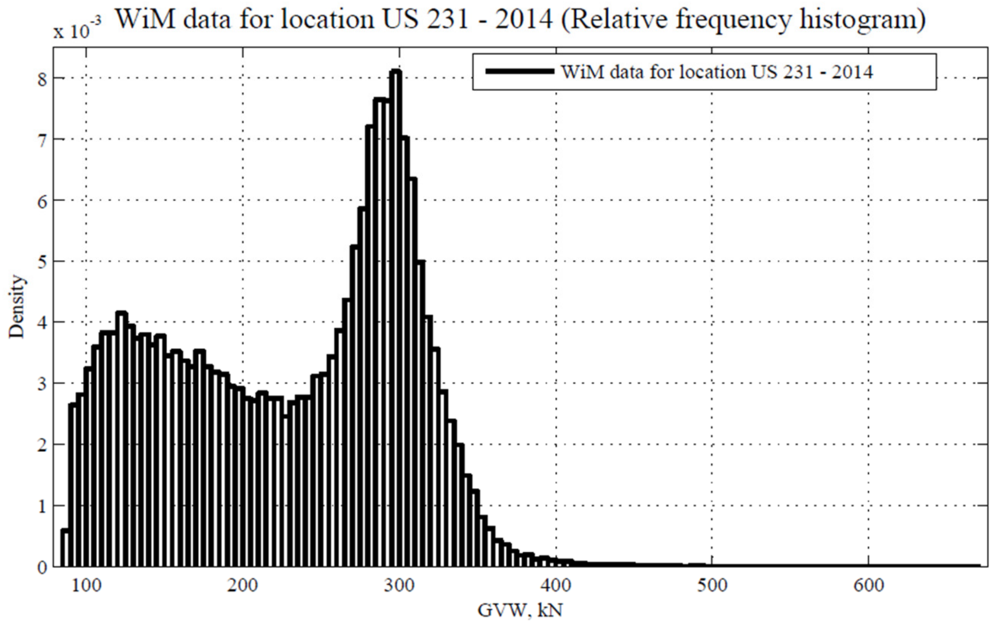

Fig. 2. Histogram of GVW for US231, year 2014

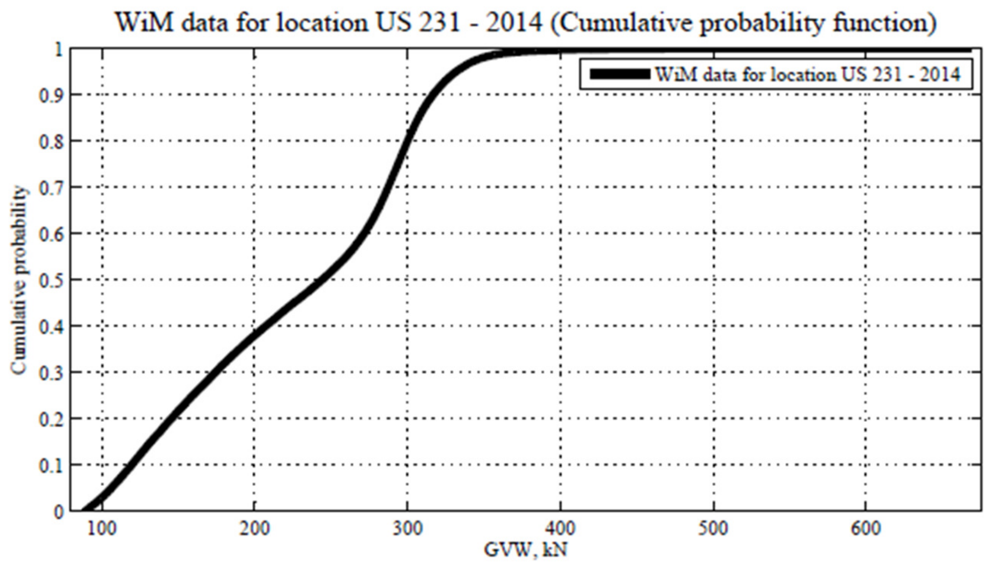

Fig. 3. CDF of GVW for US231, year 2014

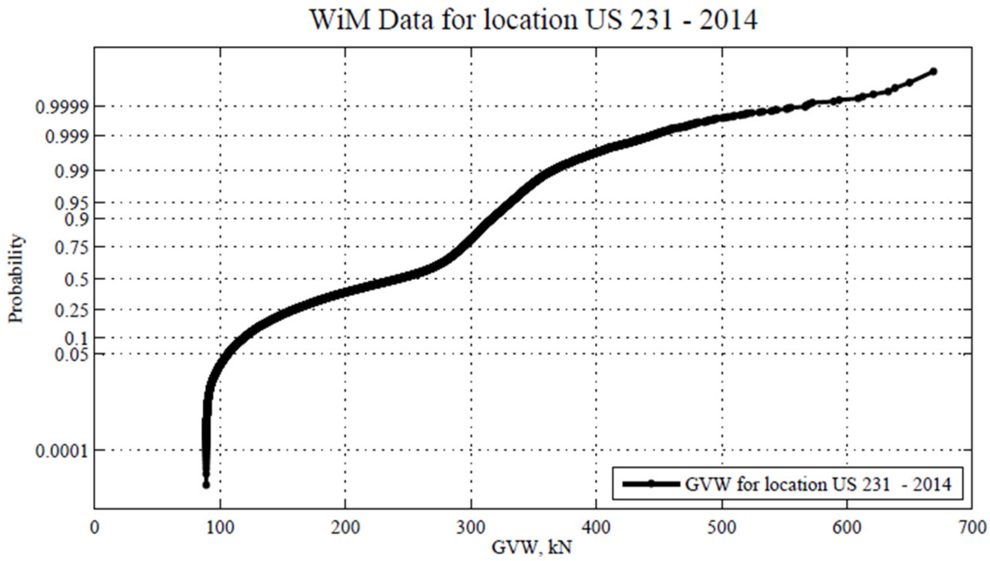

Fig. 4. CDF of GVW for US231, year 2014, plotted on the normal probability paper

Other CDF's of GVW are also plotted on the normal probability paper. In Fig. 5, an example of GVW records is shown for all locations for year 2011. The shapes of curves representing the CDF's are similar. Less than 80% of all trucks are lighter than 350 kN, about 18% are between 350 kN and 450 kN and less than 1% are above 450 kN.

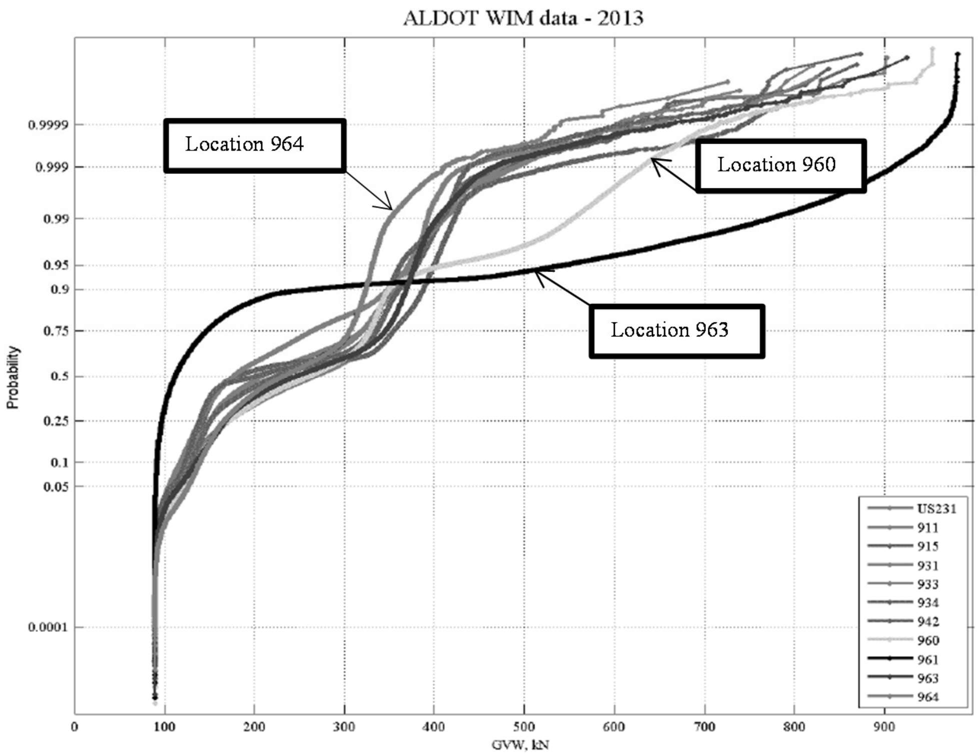

Fig. 5. CDF's of GVW for all the available locations, year 2013

The percentage is different for location 963 as shown in Fig. 5. More than 90% of the vehicles have GVW lower than 270 kN (316,466 trucks in 2013 and 476,022 trucks in 2014) and 0.15% are heavier than 900 kN. The maximum GVW is about 1000 kN.

The WIM database covers about a year for each location. Therefore, the maximum values of GVW were identified for each day, each week and each month and the resulting CDF's for location #933 are plotted on the normal probability paper in Fig. 6 for years 2009, 2010, 2011 and 2013 (records for 2012 are not available).

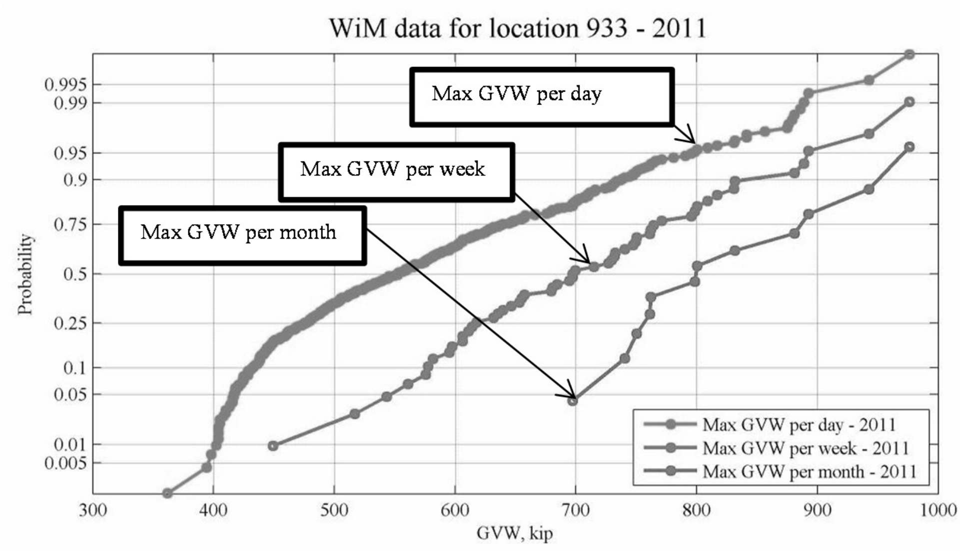

Fig. 6. Max values of GVW for location 933 and year 2011

The maximum daily GVWs are plotted in Fig. 7, and the mean values vary from 500 kN to 550 kN (year 2011). The maximum weekly GVW's are shown in Fig. 8 and the mean values vary from 600 kN to 700 kN (year 2011). The mean maximum monthly GVW's vary from 680 kN to 750 kN.

The curves representing CDF's can be used to determine not only the maximum and minimum GVW values, but the slope also provides information about the standard deviation.

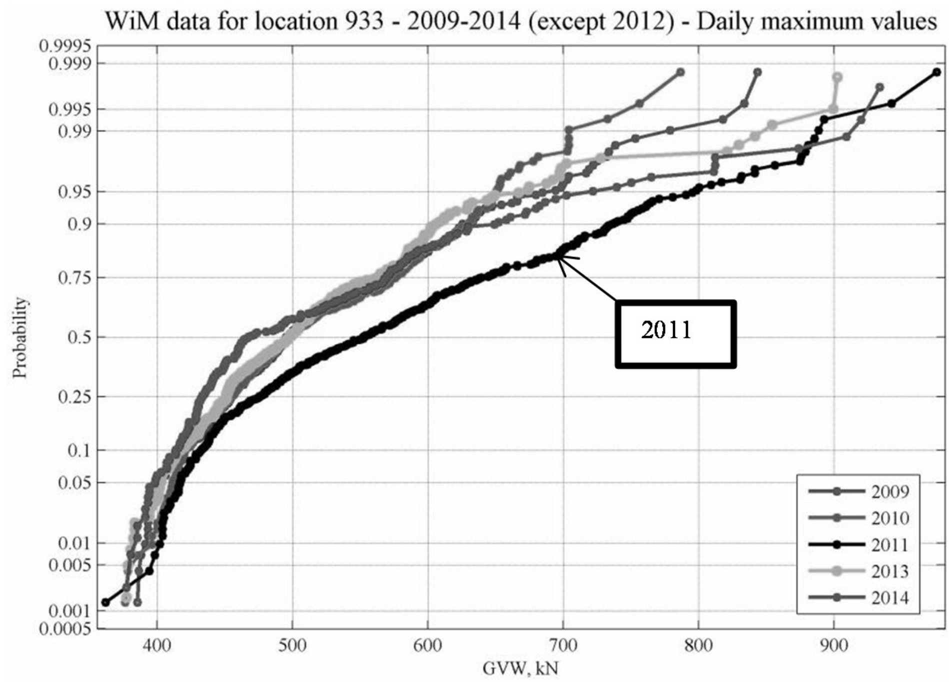

Fig. 7. Max daily values of GVW for location 933 and years 2009–2014 (except 2012)

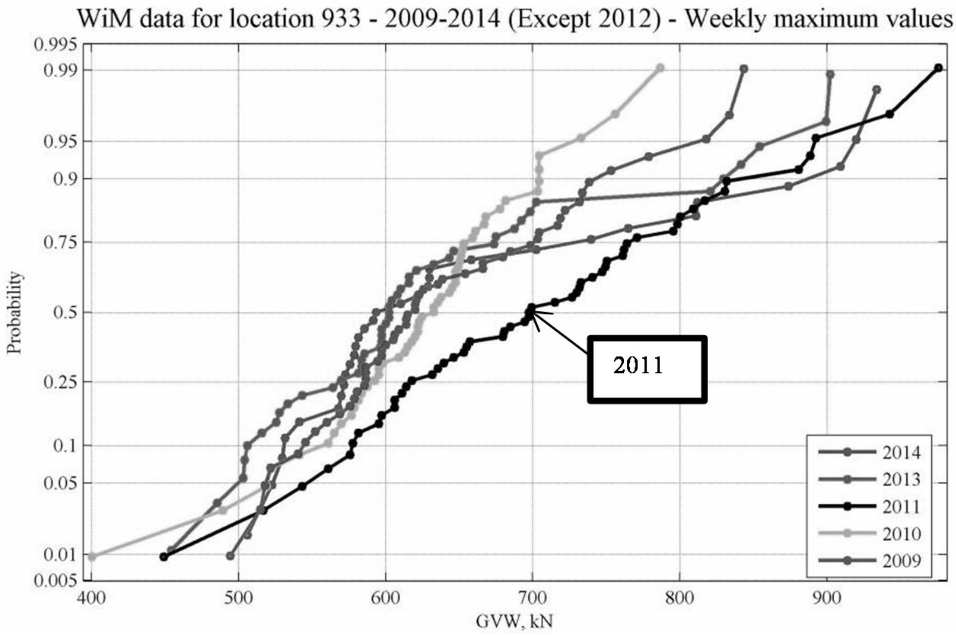

Fig. 8. Max weekly values of GVW for location 933 and years 2009–2014 (except of 2012)

For each location, the distribution of GVW strongly depends on traffic mix, in particular the dominating vehicle types. Therefore, the CDF's were considered separately for different vehicle classes as specified by the FHWA (Fig. 9). The results are shown for the most common types of trucks. The traffic mix composition was reviewed for each location and an example is shown in Fig. 10 for location 933. Class 9 (five-axle, single trailer truck) was found to be the most common not only for location 933 but also for the whole State of Alabama. The maximum value of GVW for class 9 (location 933 and year 2014) is about 920 kN, about 10% have GVW larger than 350 kN (49,127 trucks) and about 1% have GVW exceeding 450 kN (4,913 trucks). This corresponds to 8 and 0.8% of total number of vehicles for location 933 in 2014.

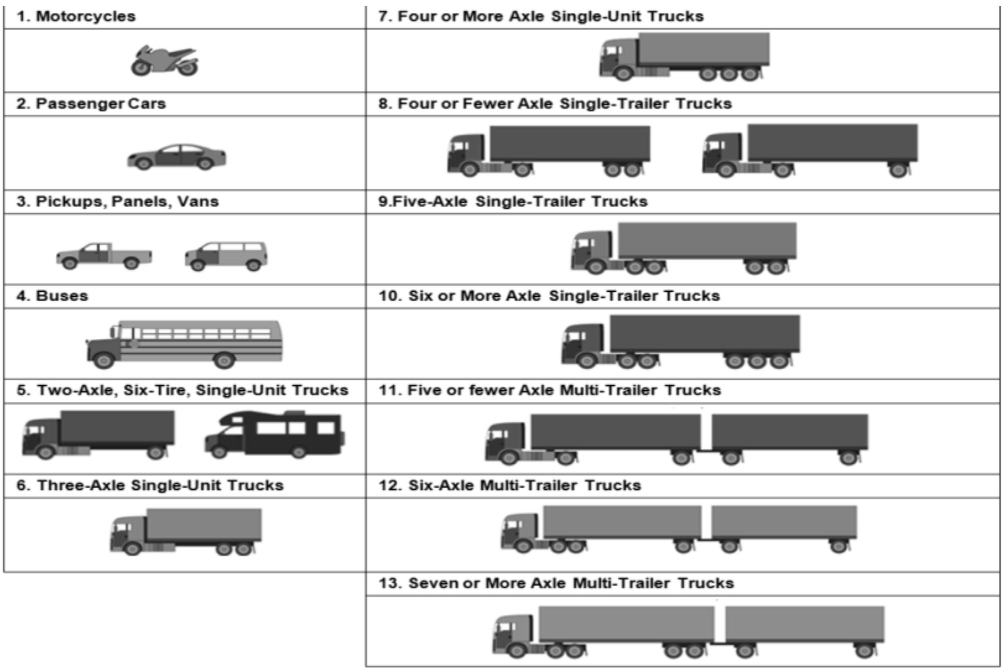

Fig. 9. FHWA vehicle classes

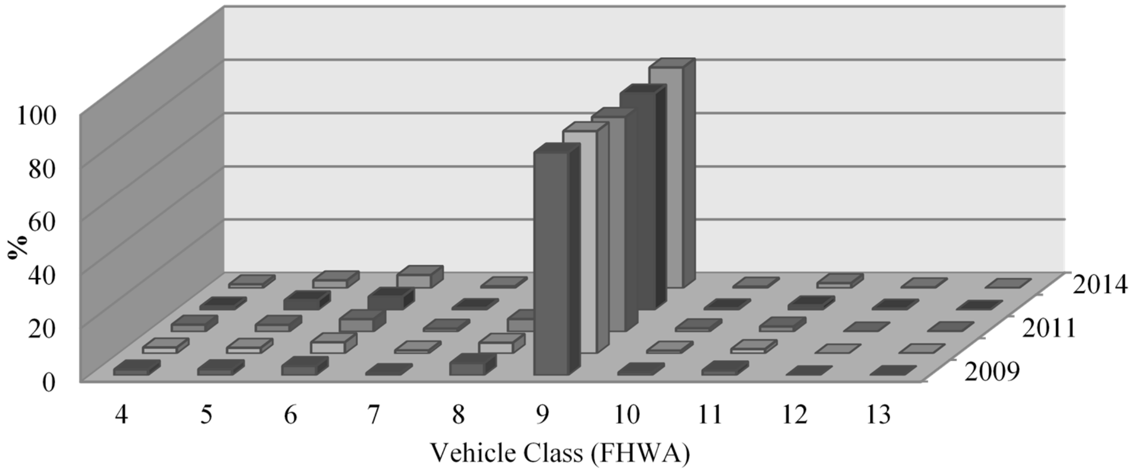

Fig. 10. Percentage of each vehicle class (933)

However, class 9 is not the dominating type for all of the other locations, as shown for example in Fig. 11 for location 963 and years 2013 and 2014. At this location, class 5 (five-axle, six-tire, single unit truck) is the most common vehicle with about 40% (434,867 trucks) out of the total number of 134,556 in 2013 and 65% in 2014. The maximum GVW value for class 5 at location 963 and year 2014 is about 260 kN. At the same time, trucks heavier than 800 kN constitute about 0.15% of the total population, which is 514 trucks in 2013 and 818 trucks in 2014.

Therefore, live load can be controlled by consideration of only a few types of vehicles.

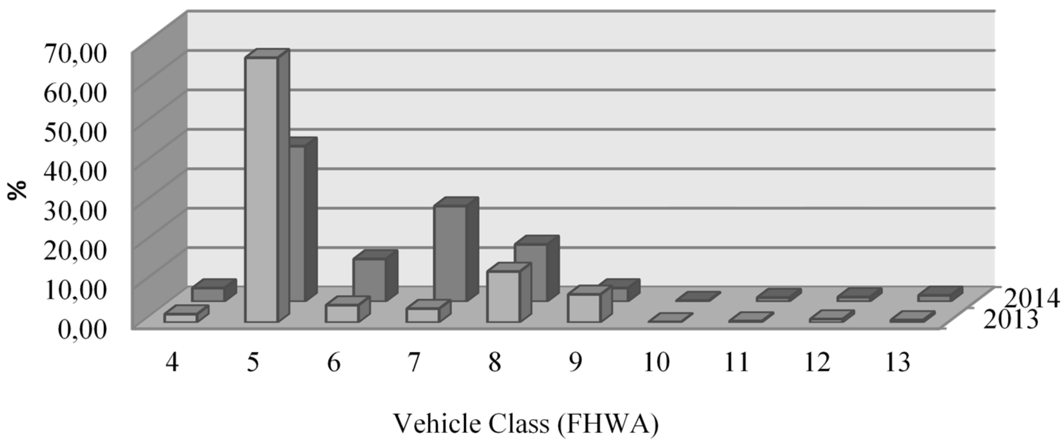

Fig. 11. Percentage of vehicle classes, location 963

4. Live load moments & shear forces

Moving vehicles can cause damage to bridge structures leading to a partial damage or even a total loss of the load carrying capacity. Therefore, it is important to identify the types of vehicles that exceed legal load limits and prevent overloaded trucks from entering the bridge.

Potential bridge damage can be considered in terms of live load effects, i.e. moments and shears. In the present study, the moments and shear forces were calculated using influence lines.

The trucks form the WIM data were run over influence lines and for each vehicle, the maximum moment and shear force were recorded. The calculations were performed for simply supported spans of 10, 20, 30, 45 and 60 m. For an easier interpretation of the results, the obtained moments and shear forces were divided by the corresponding code specified values, i.e. HL-93 live load effects (AASHTO 2015). The HL-93 live load is shown in Fig. 12.

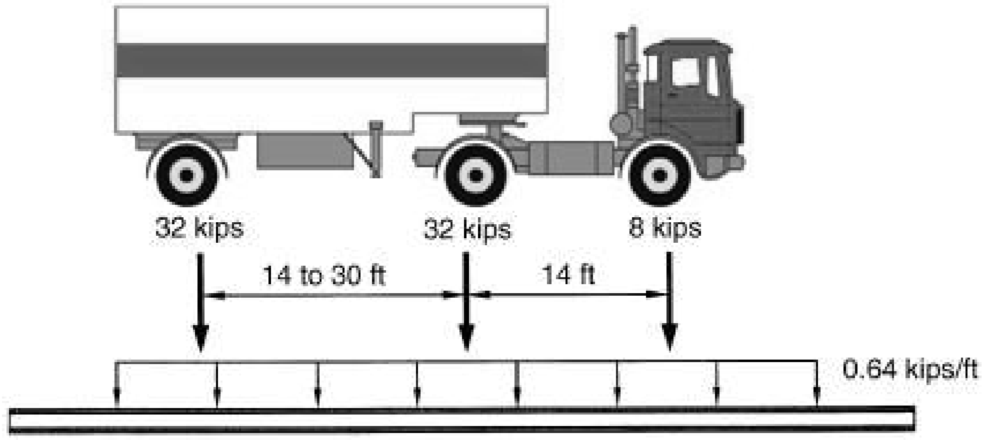

Fig. 12. HL-93 Loading (1 ft = 0.3 m, 1 kip = 4.5 kN)

The CDF's of the computed non-dimensional ratios for moments and shear forces were plotted on the normal probability paper for each location and year. The results are shown in Fig. 13 for moment ratios and span of 10 m, in Fig. 14 for moment ratios and span of 60 m, Fig. 15 for shear force ratio and span of 10 m, and Fig. 16 for shear force ratio and span of 60 m. For each location, the shape of the obtained CDF curves is very similar to that of GVW. It also can be observed, that the mean value of the ratio for both moment and shear force gradually decreases for longer spans.

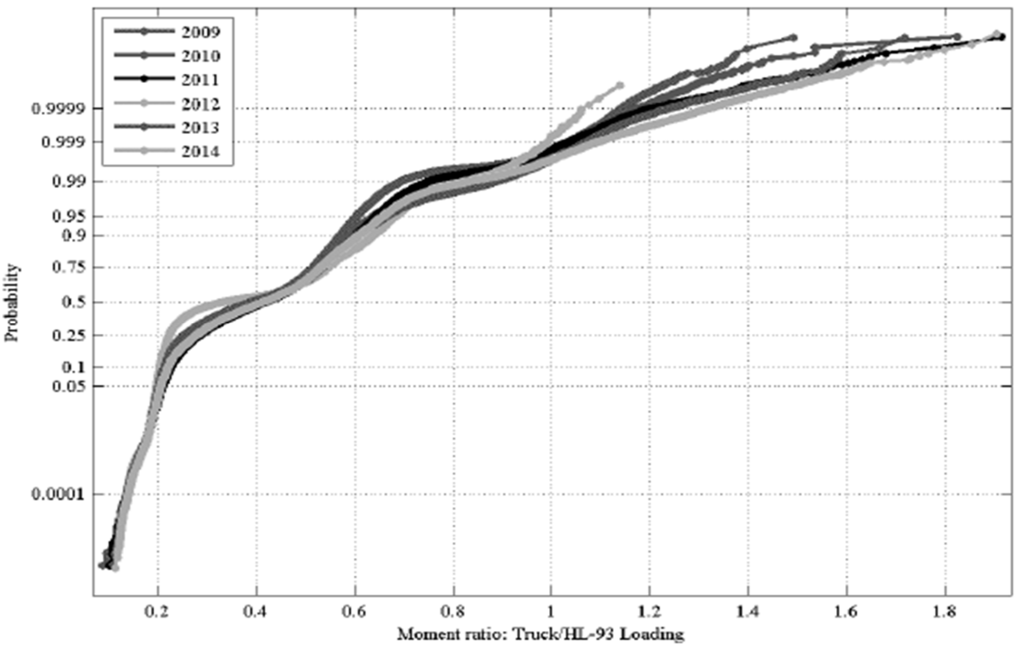

Fig. 13. CDF of moment ratio for 10 m span for all locations

Mean value for moment ratios varies from 0.3 to 0.45 for 10 m span (Fig. 13) and from 0.2 to 0.4 for 60 m span (Fig 14). The maximum value of the shear force ratio is from 1.0 to 2.4. Mean value for shear force ratios varies from 0.3 to 0.45 for 10 m span (Fig. 15) and from 0.20 to 0.35 for 60 m span (Fig 16). The maximum value of the shear force ratio is from 1.0 to 2.4.

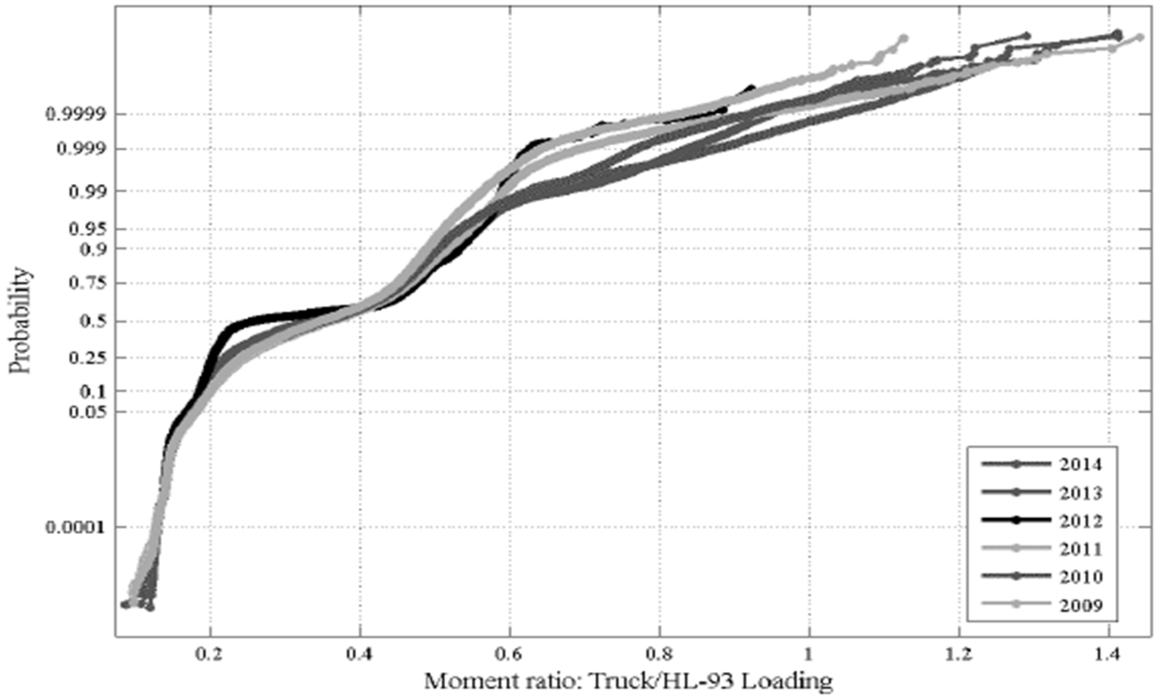

Fig. 14. CDF of moment ratio for 60 m span for all locations

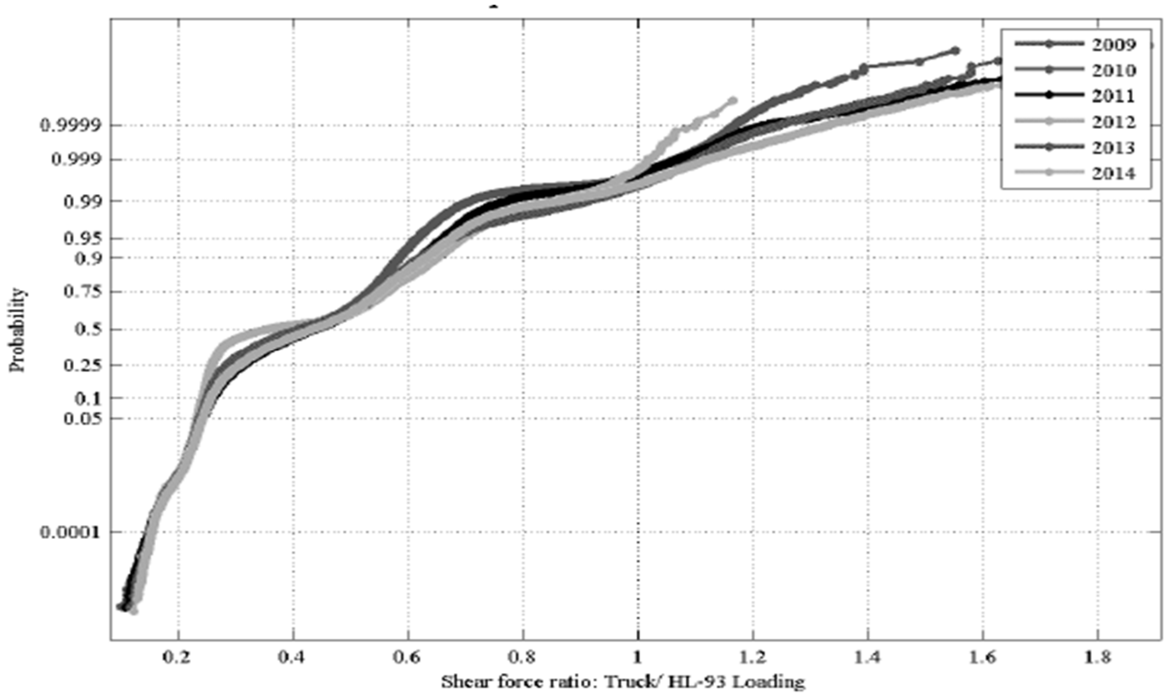

Fig. 15. CDF's for shear force ratio for 10 m span and all locations

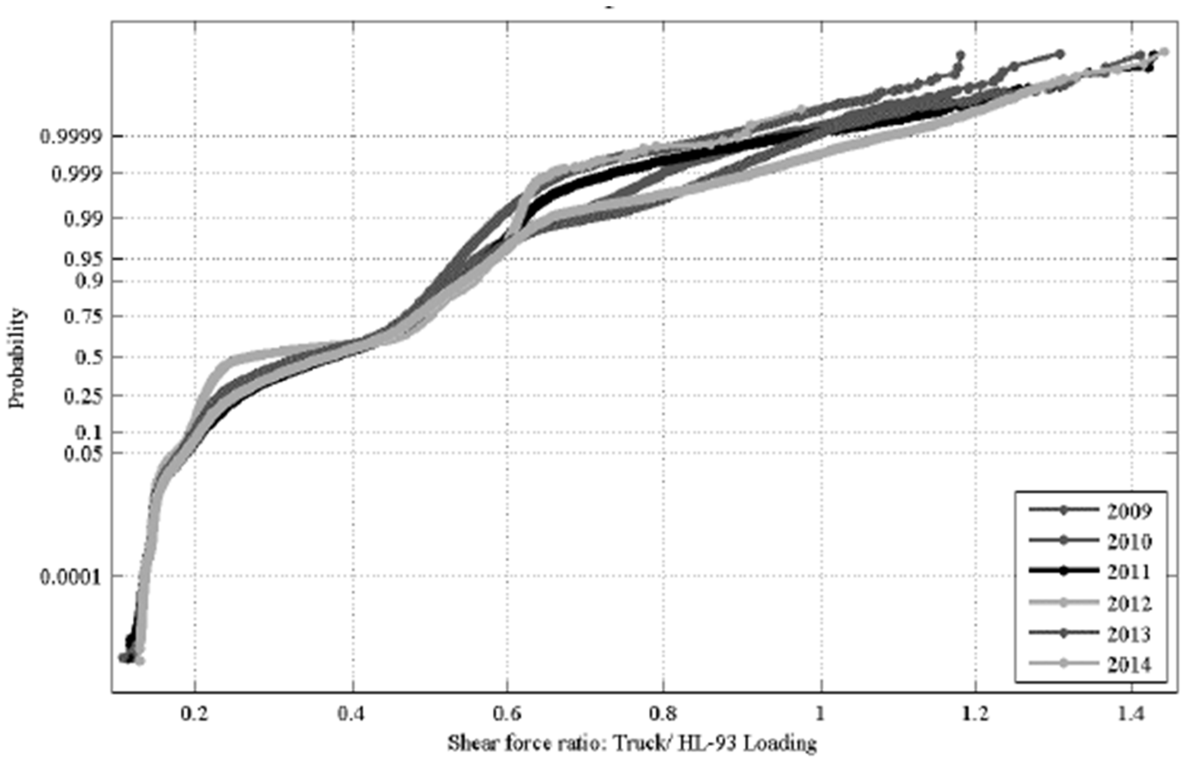

Fig. 16. CDF shear force ratio for 60 m span for all locations

As in case of the GVW data, the maximum values of moment and shear force ratios were determined per day, week and month for the considered locations and years. The resulting maximum daily CDF's are plotted in Fig. 17 for moment and span of 10 m, Fig. 18 for moment and span of 60 m, Fig. 19 for shear force and span of 10 m, and Fig. 20 for shear force and span of 60 m. Maximum values of moment ratio were plotted for all period of taken measurements for 10 m (Fig. 15) and 60 m (Fig. 16).

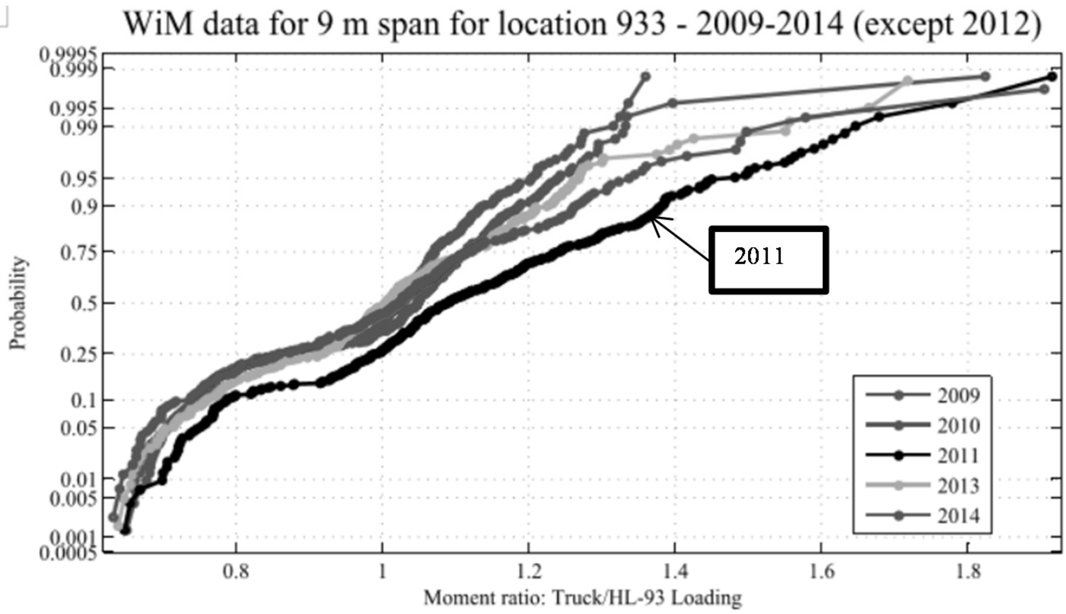

Fig. 17. Max daily values of moment for location 933 and years 2009–2014 for span 10 m (except of 2012)

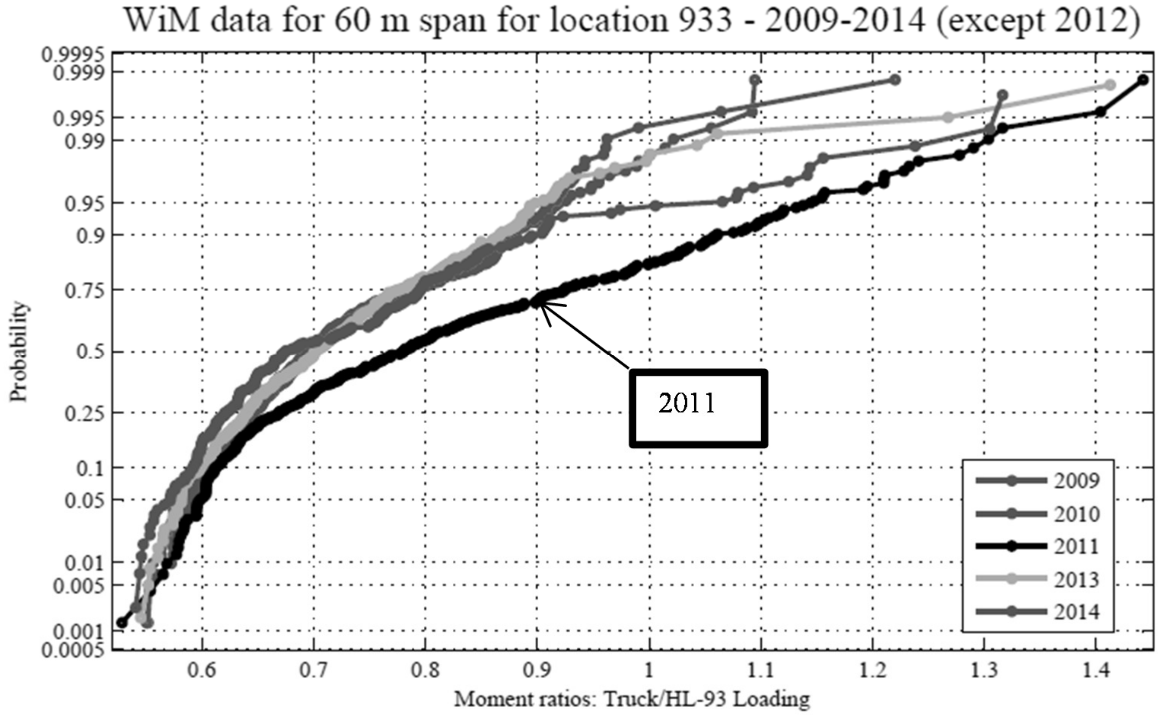

Fig. 18. Max daily values of moment for location 933 and years 2009–2014 for span 60 m

The mean maximum daily value for 10 m span varies from 0.9 (years 2009–2014) to 1.1 (year 2011), the mean maximum weekly – from 1.15–1.25 (years 2009-2014) to 1.35 (year 2011). The mean maximum daily value for 60 m span varies from 0.65 (years 2009-2014) to 0.78 (year 2011), the mean maximum weekly – from 0.75–0.82 for years 2009–2013 to 0.81 for year 2011. The variation of slope is similar to that observed for GVW.

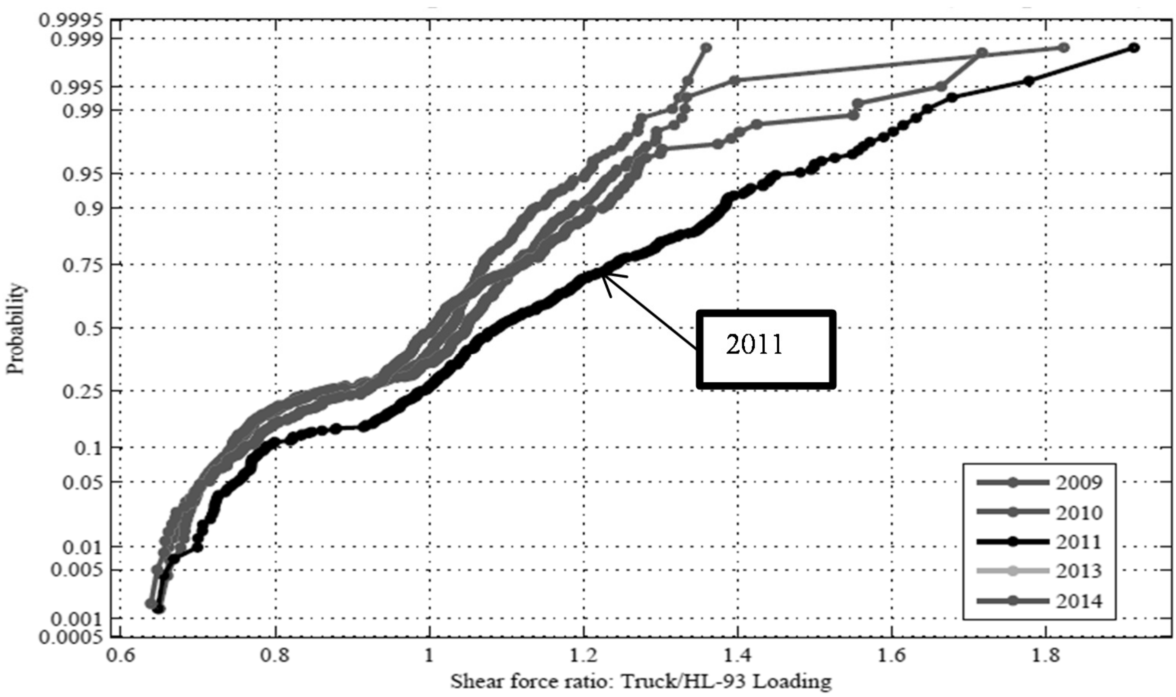

Fig. 19. Max daily values of shear force ratio for location 933 and years 2009–2014 and span 10 m (except of 2012)

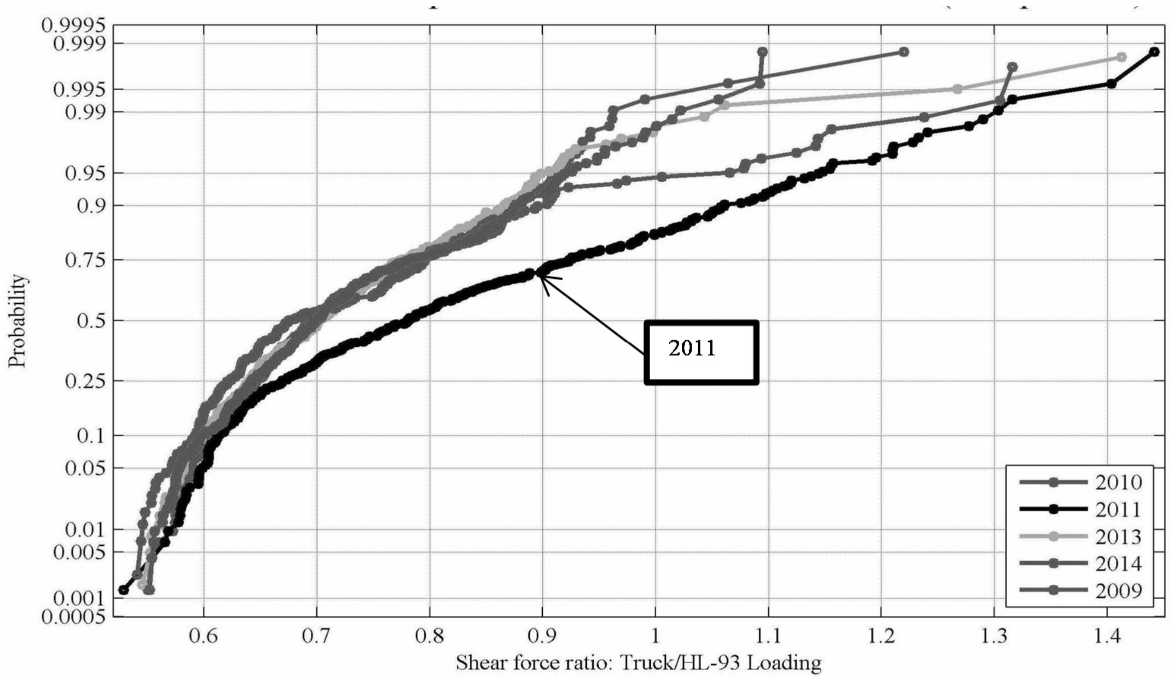

Fig. 20. Max daily values of shear force ratio for location 933, years 2009–2014 and span 60 m (except of 2012)

The mean maximum daily value of shear force ratio for 10 m span varies from 1.0 (years 2009–2014) to 1.1 (year 2011), maximum weekly – from 1.05–1.2 (years 2009–2014) to 1.3 for year 2011. For the span of 60 m, the mean maximum daily value varies from 0.7 (year 2009–2014) to 0.77 (year 2011), the mean maximum weekly – from 0.85-0.87 for year 2009–2013 to 1.0 for year 2011. The changes in the slope are similar to that of the GVW.

5. Outliers

The results for location 933 presented in Fig. 17, 18, 19 and 20 can be considered as representative for most other locations. However, the recorded WIM data for two locations US-231 and 963 was very different than everything else. These locations require a special consideration.

The CDF's of the maximum daily, weekly and monthly GVW for location 963 are plotted in Fig. 21 for year 2013 and in Fig. 22 for year 2014. From the CDF's of maximum GVW values for the 963 location it can be seen that there was a large number of days with significantly overloaded trucks. In addition, the daily, weekly and monthly maximum plots have almost the same shape (almost vertical) for GVW larger than 900 kN. This can be explained as the same heavily loaded trucks were selected and recorded as the heaviest for day, week and month. This was the location where the heaviest vehicles were recorded.

However, the percentage of heavily loaded trucks is relatively small in comparison to the other locations, as it is less than 0.01%. In other words total number of trucks with GVW larger than 900 kN varies:

– from 57 to 169 trucks per month (3 per day average) in 2013;
– from 47 to 105 trucks per month (2 per day average) in 2014;

The lower tail of CDF in Fig. 21 with GVW less than 450 kN represents the days of the year with no heavy truck traffic. For this location, there are exceptionally many vehicles that are short and heavy.

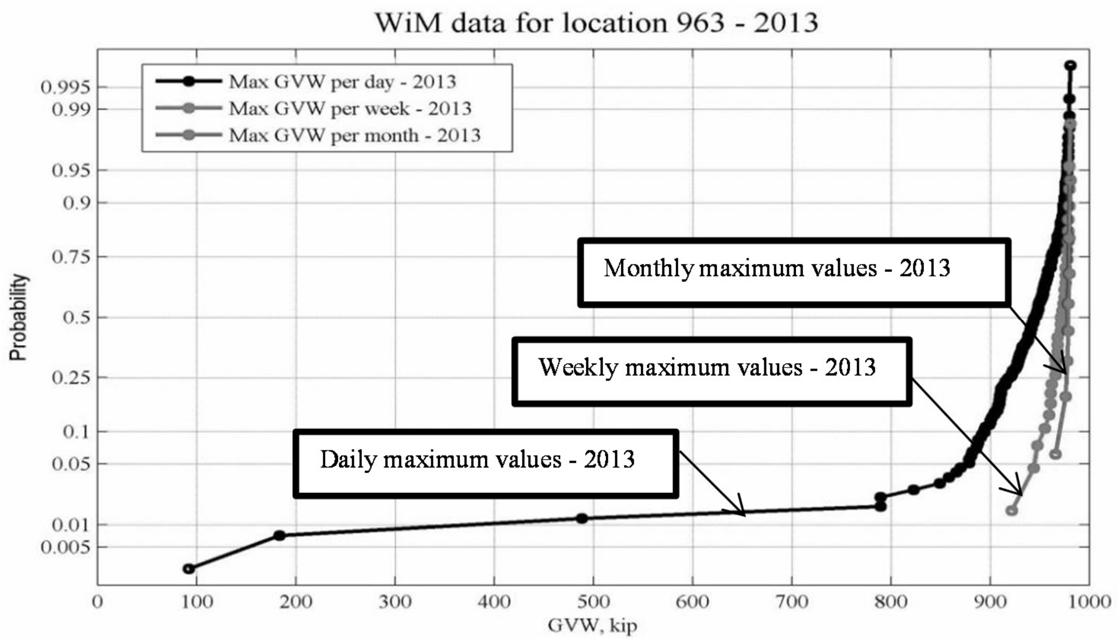

Fig. 21. Max values of GVW for the location 963 2013

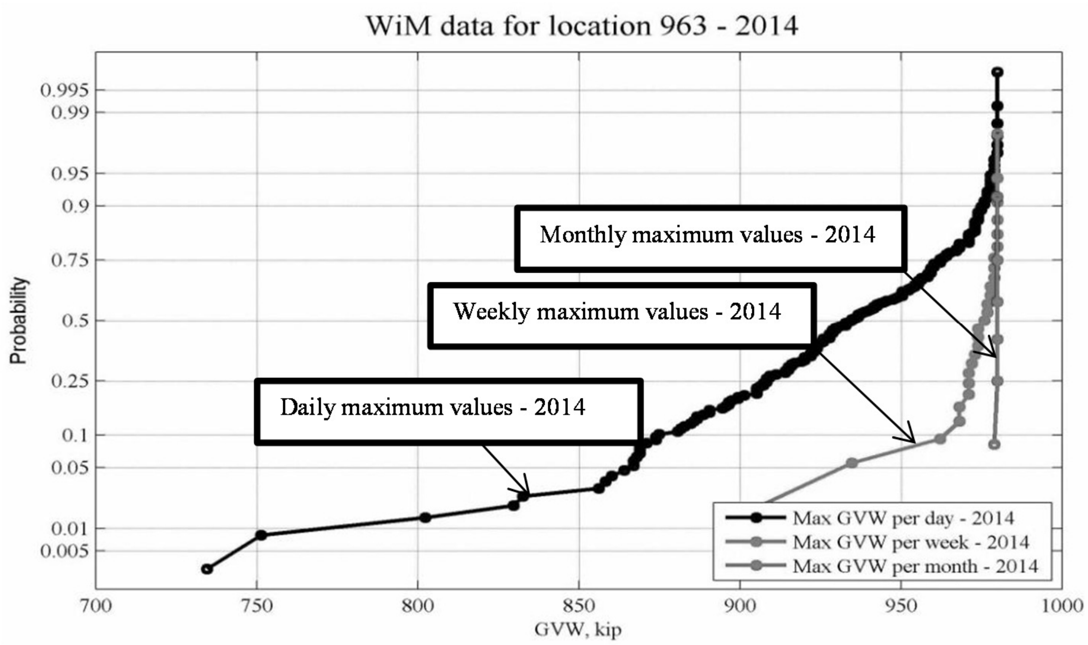

Fig. 22. Max values of GVW for the location 963 – 2014

The moment and shear force ratios for location US-231 are plotted in Fig. 23 for moments and 24 for shear forces. The mean value for the moment ratio varies from 0.3 to 0.5 for all considered span lengths except of two locations: US-231 and 963. It was observed that for other locations, 1–5% of vehicles exceed the moment ratio of 1.5 (i.e. 1.5 of the HL-93 moment), but for US-231 the ratio is 2.4.

Thus, the mean value of moment ratios for all available data (through whole period of taking records) is 0.45 for 10 m span and 0.35 for 60 m span. The maximum value of moment ratio is 1.9 for 10 m span and 1.5 for 60 m span. This indicates that for longer spans live load is distributed more uniformly.

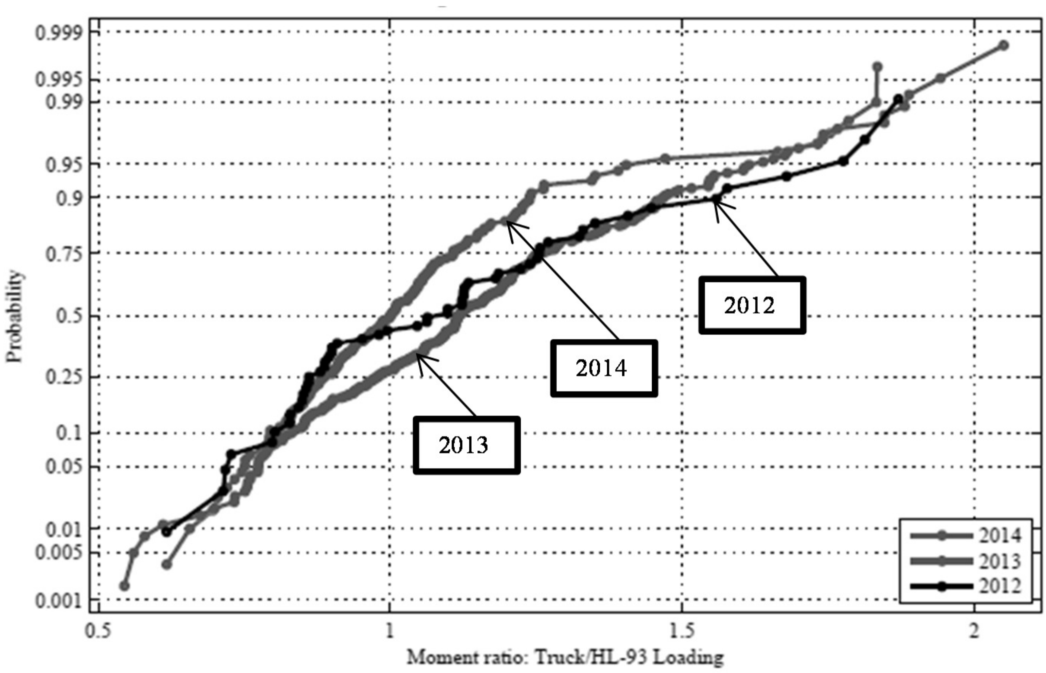

Fig. 23. Max values of moment ratio per day for 10 m span for the location US 231 for 2012– 2014

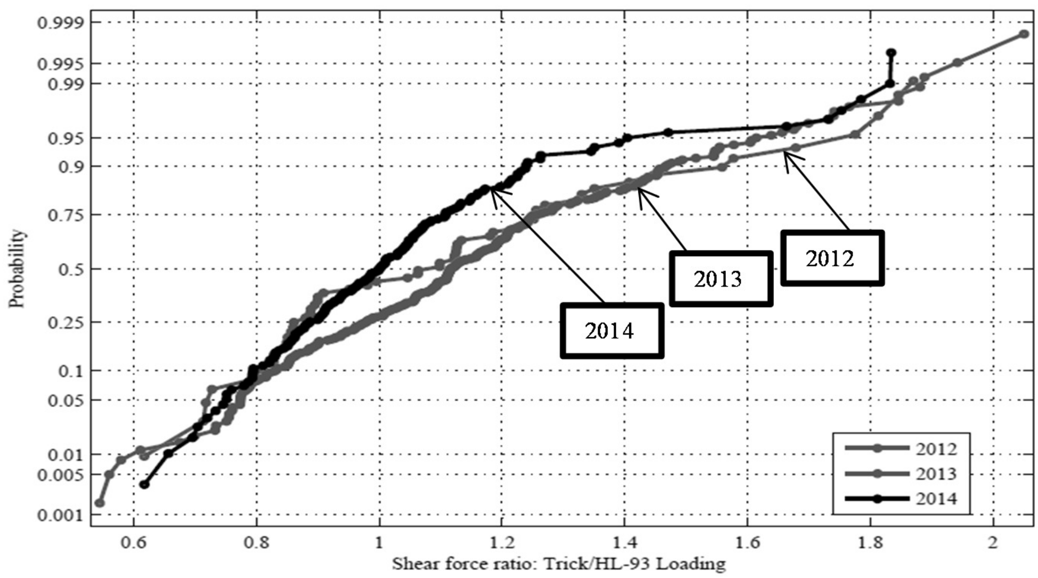

Fig. 24. Max values of shear force ratio per day for 10 m span for the location US 231 for 2012– 2014

The mean value of the shear force ratio varies from 0.2 to 0.4 for all other considered span lengths. For US-231, the maximum value of the shear force ratio is from 1.0 to 2.4.

Live load parameters such as GVW, bending moment and shear force ratios are very sensitive with regards to the span length. In particular, special consideration is required for shorter spans. For location US-231, the maximum moment ratio for 10 m span is 2.2 (the mean value is 1–1.1) (Fig. 23), the maximum shear force ratio for 10 m span is 2.2 (the mean value is 0.95–1.15) for year 2012 and 2014, respectively (Fig. 24). The mean and maximum values of GVW are 90 kN and 1000 kN, respectively.

Moments strongly depend on truck axle configuration and total load distribution on axles rather than on magnitude of the GVW itself. The reason is that most of the overloaded trucks belong to class 9–13, with a total length of more than 10 m. Therefore, in most cases, all loaded axles cannot be within a short span simultaneously and only a portion of the truck weight can affect the actual live load. Otherwise, short vehicles (less than 10 m in this case) regardless of the class should be considered more carefully.

For location 963, the maximum moment ratio for 10 m span is 2.2–2.4 (the mean is 0.3–0.4) (Fig. 25), the maximum shear force ratio for 10 m span is 2.2–2.4 (the mean is 0.3–0.4) for year 2013 and 2014, respectively (Fig. 26). The mean and maximum values of GVW are 110 kN and 1000 kN, respectively.

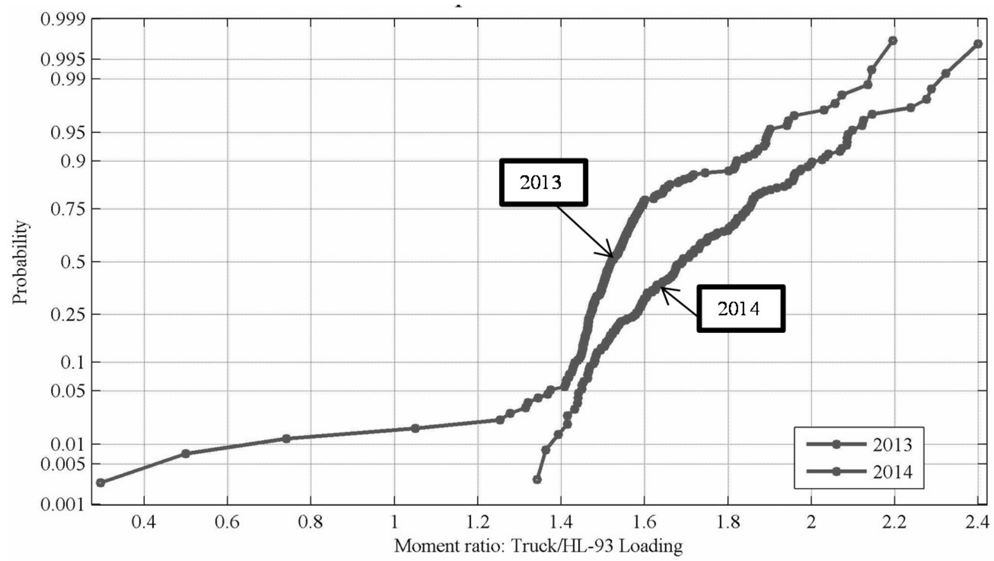

Fig. 25. Maximum daily moment ratio for 10 m span for location 963 for 2013–2014

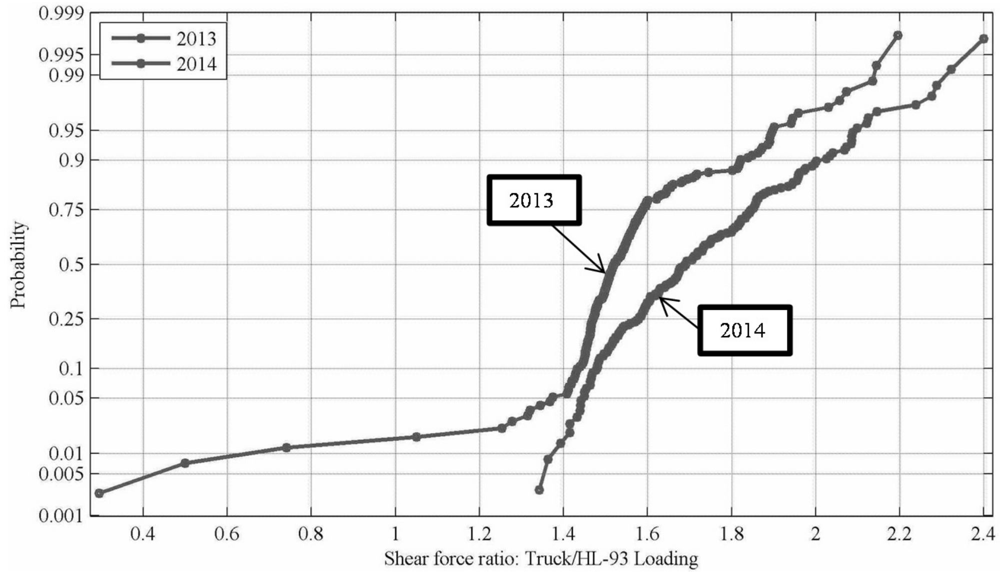

Fig. 26. Maximum daily moment ratio for 10 m span for location 963 for 2013–2014

The WIM data for the two special locations 963 and US-231 was reviewed to identify and separate vehicles with GVW over 450 kN and total truck length less than 10 m. The CDF's for the selected vehicles are plotted in Fig. 27 for GVW and vehicle class 6, Fig. 28 for vehicle class 7, Fig. 29 vehicle class 8. The number of trucks that satisfy the selection criteria is shown in Table 3 for vehicle class 6, Table 4 vehicle class 7 and Table 5 for vehicle class 8.

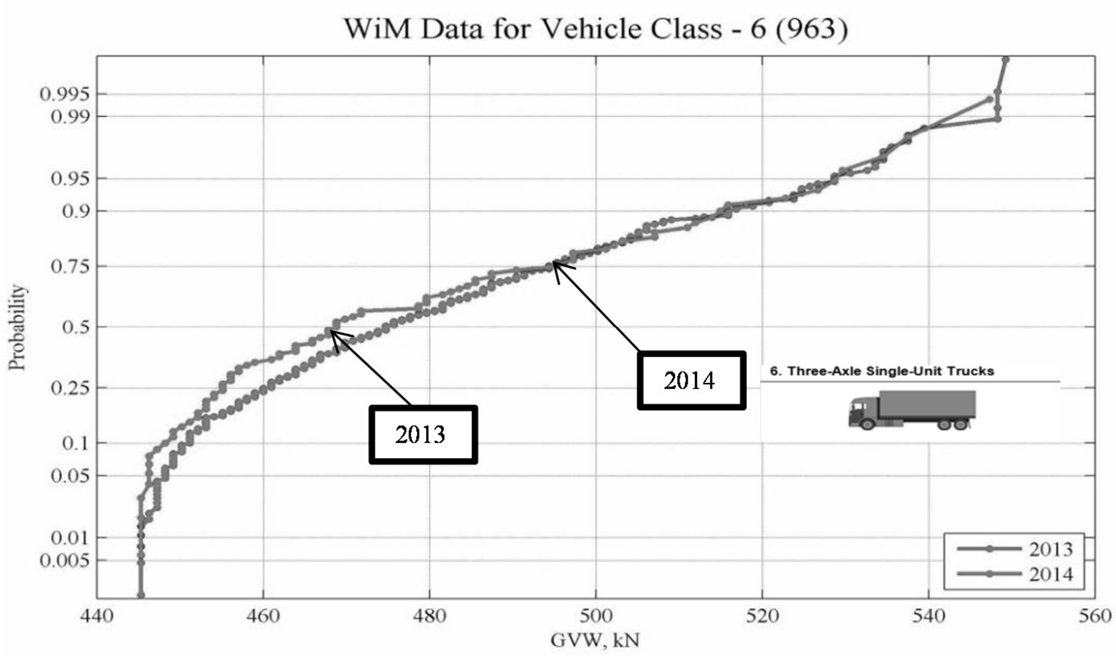

Fig. 27. CDF for GVW, vehicle class 6, for location 963

Table. 3. Number of trucks that satisfy the criteria: GVW > 450 kN and total truck length L< 10 m

	Class 6	
2013	327 trucks	0.064%
2014	85 trucks	0.025%

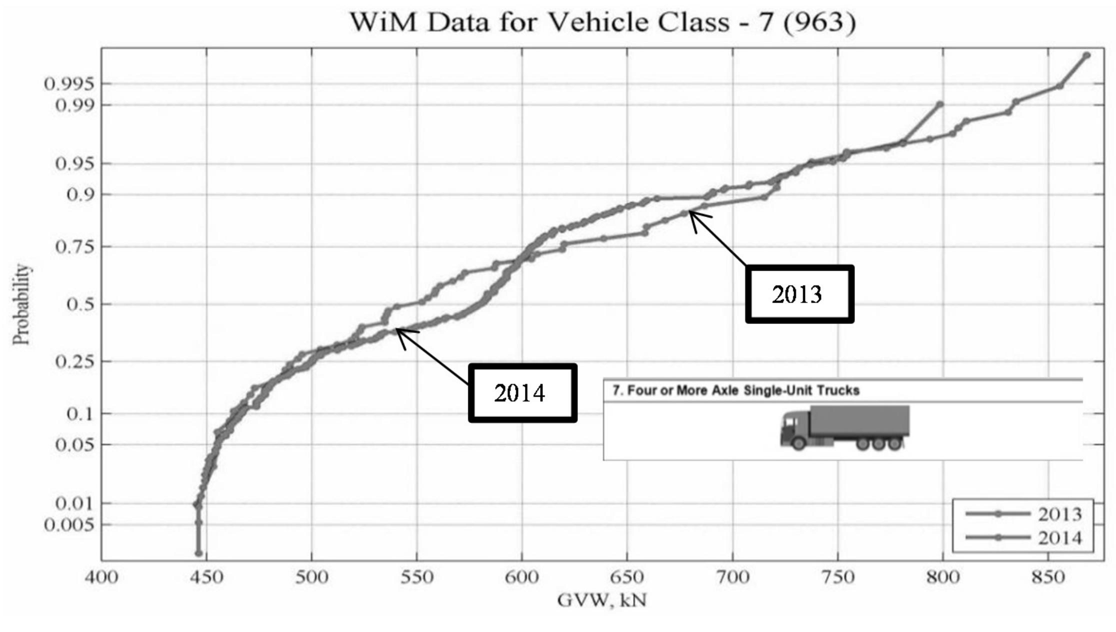

Fig. 28. CDF for GVW, vehicle class 7, for location 963

The number of vehicles that satisfied the requirements is relatively small – about 1000 trucks per year (0.16% per year), but the maximum GVW of these trucks is about 1000 kN. The corresponding moment and shear force ratio is up to 2.4. Therefore, it can be concluded that the damaging effect caused by these trucks can be quite considerable, especially as short span bridges are often in poor conditions and located in rural areas.

Table. 4. Number of trucks which satisfy the criteria: GVW > 450 kN total truck length L< 10 m

	Class 7	
2013	52 trucks	0.01%
2014	281 trucks	0.082%

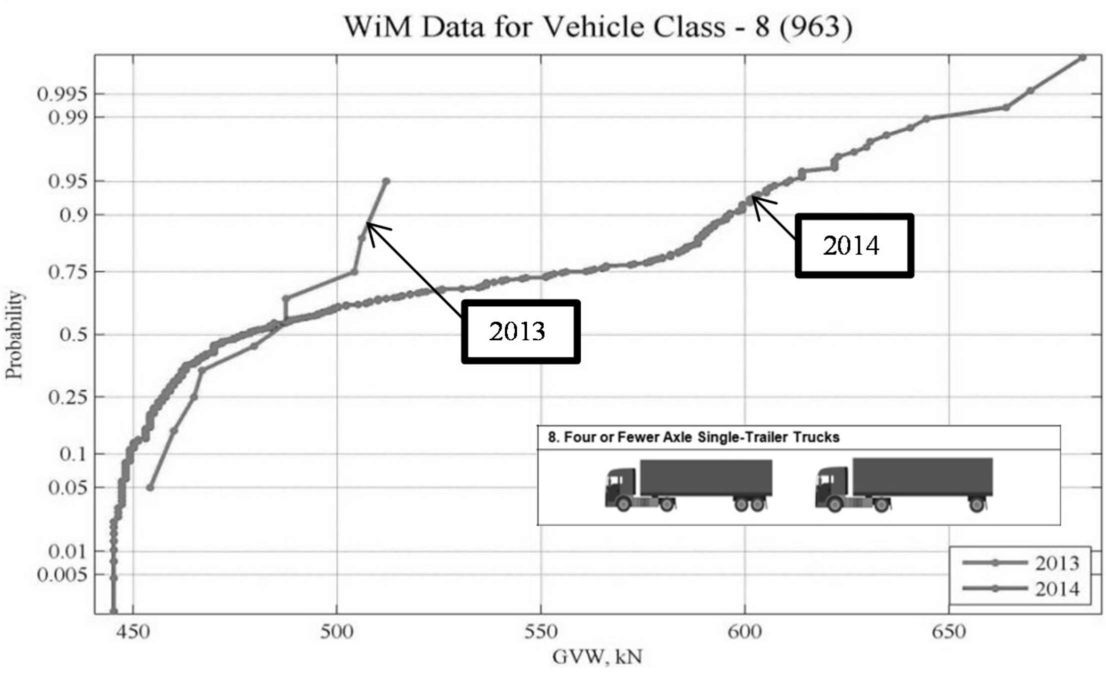

Fig. 29. CDF for GVW, vehicle class 8, for location 963

Table. 5. Number of trucks which satisfy the criteria: GVW > 450 kN total truck length L< 10 m

	Class 8	
2013	10 trucks	0.0002%
2014	337 trucks	0.1%

6. Conclusions

The data base for the presented study included about 35 million trucks. The considered data covers all regions and can be considered as representative for the state. The following conclusions result from the research:

– CDF's of the recorded data are mostly consistent with regard to shape, which allows generating a representative live load distribution pattern for the state. Nevertheless, the differences in truck load magnitude were considered, identified and analyzed;
– The maximum GVW was recorded at locations: 931, 933, 934 and 963. At the same time the maximum moment and shear force ratios were determined for locations: US-231 and 963. This discrepancy is caused by a certain number of relatively short and heavily loaded trucks recorded at locations US-231 and 963;

Short and heavy trucks are identified as a potential cause of damage for short span bridges.

References

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