THAI TRUCK LOADING MONITORING USING BWIM SYSTEM

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Abstract

Actual truck loads data is vital for bridge rating, and development of bridge design load. In Thailand, bridges have been designed using the HS20-44 design truck according to the AASHTO code; however, the actual truck loads are usually greater than the design truck load from the code. In addition, actual truck load are not available data to develop local truck load model for bridge design. This paper presents truck loads in Thailand that have been monitored using Bridge Weight-In-Motion (BWIM) system which innovated by author. Seven truck types are derived. Nominal analysis for simple span bridges shows that the heaviest Thai trucks induced forces are greater than that of the HS20-44 design truck.

Keywords: Bridge, Local truck load, Truck monitoring system

Introduction

Recently, structural design methods have been developed to reach greater accuracy, safety, durability, and economy. To meet this requirement, the design load is played important role, while bridges in various countries may be subject to different levels of loading from design truck load. Sometime the design specification for truck loads does not match the actual loads of local trucks. This issue is critical when the actual truck loads are higher than the design load. Bridges subjected to overloading have increased risk of damage, a shorter service life, and failure.

In Thailand, the design truck load has become a major issue [4, 12]. For many years, most bridges were designed using the HS20-44 design live load in the AASHTO code. In reality, trucks in Thailand do not resemble the design truck. The legal limit for transportation truck loads in Thailand is also clearly different from that in the United States. In addition, many trucks in along the highway have loads exceeding the legal limit4). Modern trucks are also different and tend to have greater loads than older trucks. Moreover, many bridges are old and deteriorated. The effect of actual truck loads on bridges in Thailand has yet to be investigated because no loading model for Thai trucks exists for evaluating the bridges. To developing truck load models, it requires large data of actual trucks from long time monitoring. In Thailand, truck load data is usually using stationary weighing scales at fixed locations on a few major highways. This limits the amount of data that is collected, and the data tends to be for trucks that are lighter than usual. The truck load monitoring system and truck load data are very vital for evaluating existing bridges, and developing local bridge design truck model in Thailand.

In recent year, the most popular techniques for truck load monitoring is the Bridge Weigh-In-Motion (BWIM) system [8, 13, 16] system. The BWIM system weighs the trucks as they travel across a bridge. It is popularly used in the United States, Canada, Australia, and many European countries [11, 16]. The conventional BWIM system consists of strain gauges attached to the bottom of a bridge at midspan and tape switches placed on the bridge's road surface to detect truck axles [8]. The main problem with traditional system is the axle detector such as the accuracy of estimation axles spacing, the devices exposing to roadway which leads to poor durability, difficult and unsafe installation and maintenance. Many studies have developed a Free Axle Detector system (FAD) [10, 17] which this technique needs appropriated bridge component to installation transducer for axle detector.

This paper is using alternative BWIM technique which innovated by author for monitoring truck loads at Highway in Bangkok. The system in this study includes strain transducers (strain gauges), photoelectric sensors to detect truck axles, and a CCTV. Using photoelectric sensors can get rid equipment exposed on the road surface, increase accuracy in estimation axle spacing which increase accuracy of the system, and inexpensive. The loads and configurations (number and spacing of axles) of trucks in Thailand that have monitored using this system are presented. The paper also primarily compares the heaviest monitored Thai truck with the standard design truck (HS20-44) in the AASHTO code.

Overview of the System

Principal BWIM Algorithm

The concept of the BWIM algorithm is that the bridge will be deformed proportional to the applied axle truck load. This deformation is measured by strain gauges attached to the bottom surface (girder or slab) of the bridge. The positions of the truck's axles are measured by axle detectors. The bridge strain and axle data are then converted to determine the axle load. This system was first developed by Moses [7]. At recent years, several studies have improved this system, while many of these are adopted new devices and programs. The main concept of estimating the axle load is identical to Moses' concept, which minimizes the error between the theoretical influence lines and the on-site measurements (moment or strain), because this technique is not complicated and can provide acceptable results. This study also adopts the same technique of deriving the axle load. This technique is outlined below.

When a truck crosses the bridge, the locations of the truck's axles shift over time. The theoretical moment and measurement moment at the same location can be obtained, than the error function between the theoretical moment and the measured moment can be set up as Equation (1).

$$\varphi = \sum_{k=0}^{T}\left[\sum_{n=1}^{N} P_n I(x_n(t_k)) - M^*(t_k)\right]^2 \tag{1}$$

Where $\sum_{n=0}^{N} P_n I(x_n(t_k))$ is the theoretical bending moment at the location of the measurement. P_n is the axle load at location x_n. t_k is the time with reading increment number k. $I(x_n(t_k))$ is the influence line ordinate in the function of time corresponding to the axle load at x_n. $M*(t_k)$ is the measurement moment. where T is the number of scans taken as a truck crossing the bridge. Minimizing function φ , would produce a matrix of system equations for the unknown axle load.

Solving these equations yields the axle load, P_n. The gross vehicle weight (GVW) is the sum of the axle loads.

The Instrumented Bridge

The tested bridge in this study is located on the Bangkok Eastern Ring Road (BK-ERR) in the eastern part of Bangkok. This is the main highway linking between Thailand's southern and north-eastern (NE) regions (Figure 1). Most heavy trucks use this highway to avoid entering the city centre.

Since most of the bridges on this highway are prestressed concrete (PC) bridges, a PC I-girder bridge was selected for this study. The bridge has 6 girders, as shown in Figure 2(a), a total length of 20 m, a support span of 19.4 m, and a total width of 11.9 m, as shown in Figure 2(b). The bridge has two lanes of traffic with 3.5 m in width and trucks running in the same direction. The sidewalk is 2.4 m wide and located above G1, from left to right. The road surface is very smooth. Traffic is very heavy, especially during the day.

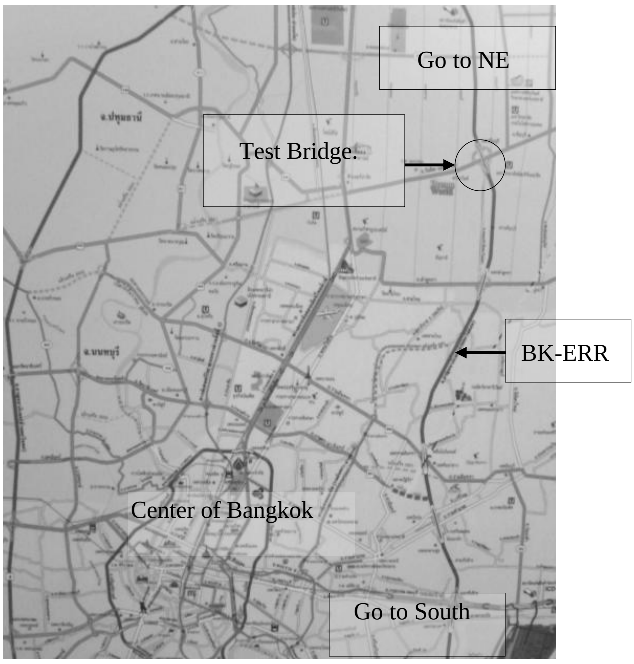
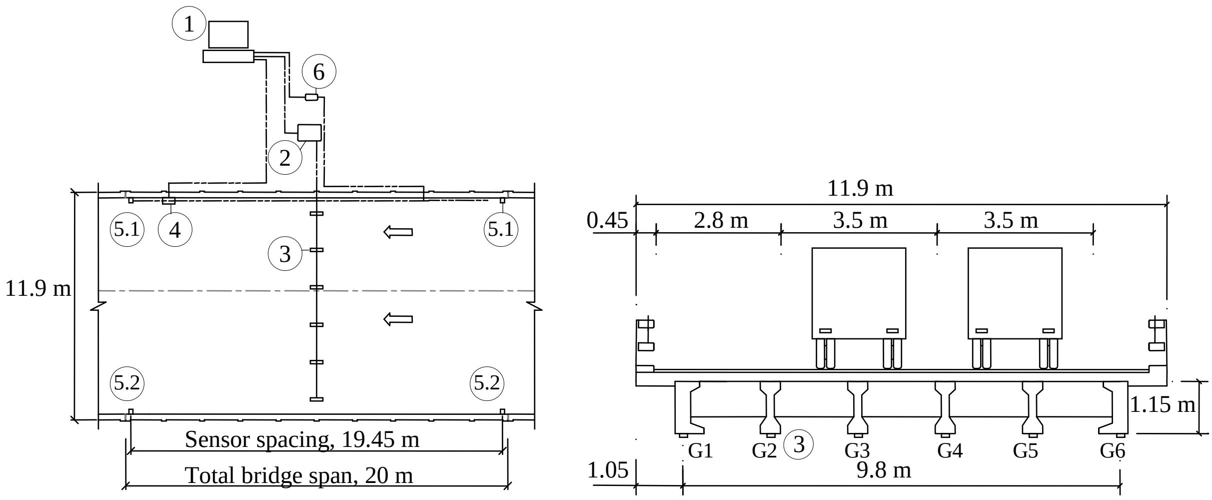


Figure 1**.** Location of tested bridge

System Equipments/Devices and Installation

The devices of the system include a computer, strain gauges, a data acquisition (DAQ), CCTV, photoelectric sensors, and DAQ for the photoelectric sensor. Figure 2 shows positions of the devices on the tested bridge.

Cracks are not allowed in prestressed concrete bridges, therefore two concrete strain gages were installed on the bottom of each girder at the midspan section. The concrete strain gauges are easily to install on PC bridges and not damage the bridge girders. A data acquisition unit (DAQ) was use to record the strain signal by a sampling rate of 1 kHz. This strain data was then filtered the noise using a separate program by a low-pass filter. Two sets of photoelectric sensors were installed for detecting truck axles. The sensors were attached to the bridge parapets (25 cm above the road surface) at both ends of the bridge as shown in Figure 2 (devices number 5.1 and 5.2). These sensors provide signal, and time of each wheel truck when it enters and out off the bridge. By assuming that the truck's velocity is constant, then truck's velocity and axle spacing can be estimated. The CCTV was installed on the bridge side to record trucks crossing the bridge.



a). Locations of devices on bridge

b). Cross section of bridge

1 PC computer

2 DAQ for strain gages

3 Strain gages

4 CCTV

5.1 Photo electric sensor, emitter

5.2 Photo electric sensor, receiver

6 DAQ for sensor signal

Figure 2. Tested bridge

Figure 3 shows an example of a signal of 3-axle truck. is the time between the first sensor detecting the first axle and the second sensor detecting the same axle, is the time between axle one and axle two at the first sensor, is the time between axle two and axle three at the first sensor, and is the time indicating the width of the truck wheel at the level of the sensor beam. The width of the truck wheel at the level of the sensor signal also can be used to classify the vehicle as a large truck (80-90 cm), small truck (70-80 cm), or pick-up or small car (less than 70 cm). The truck configuration and type can then be derived according to these data.

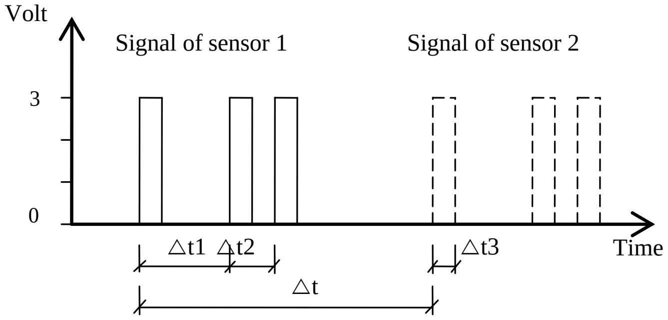


Figure 3. Example of axle sensor signal for a 3-axle truck

Accuracy of System

The stiffness of bridge girders was obtained from construction drawings, on-site measurements, and actual calibration by running truck. A 3-axle truck with a known load and axle configuration was used for calibrating the system. The calibration truck passed over the bridge twelve times, eight times in the left lane and four times in the right lane, at four different speeds. The results of this calibration were compared to the results of theoretical calculations. The calibration factor for the actual bridge stiffness is 1.30. From the calibration truck, the error in axle spacing was less than 1.5%, the error in the single axle and axle group (for closed spacing axles) weights were less than 13%, and the error in gross vehicle weight (GVW) was less than 10% as shown in Figure 4.

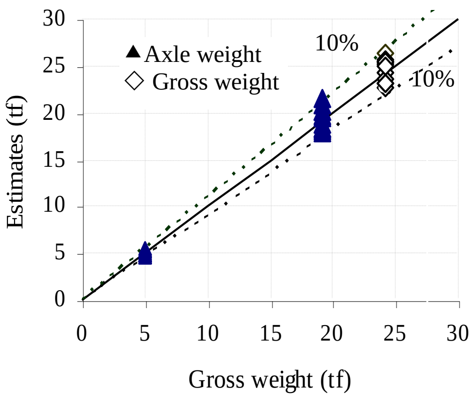


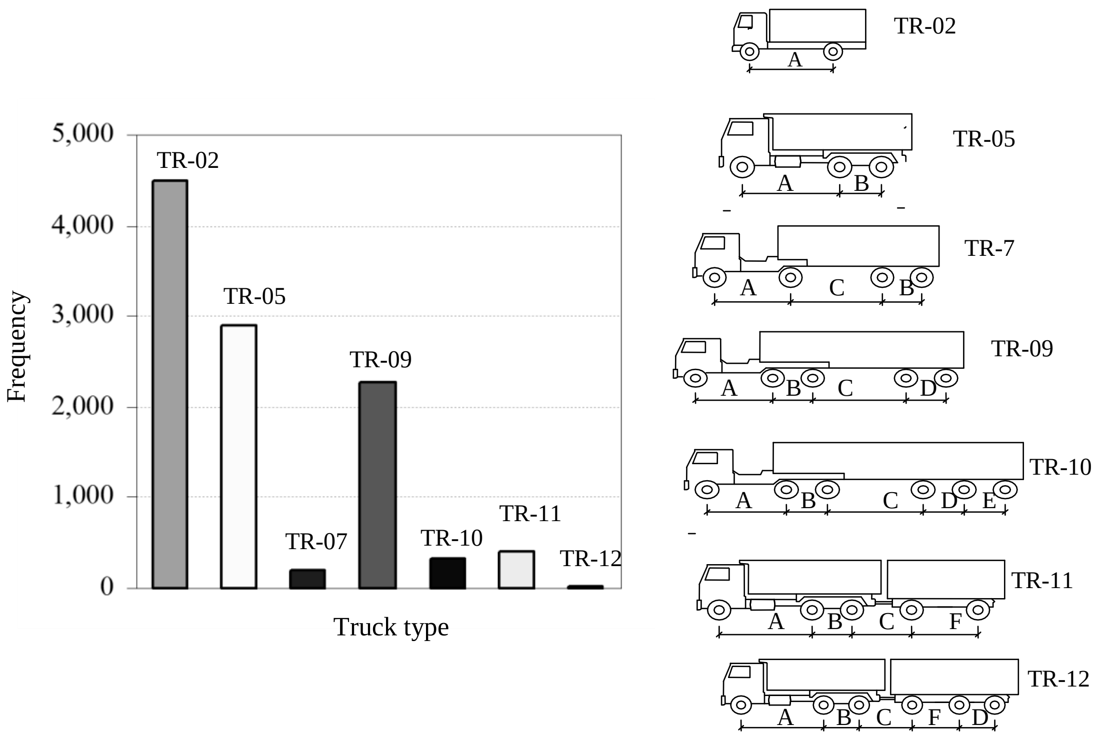
Figure 4**.** Evaluation of truck weight

Results of Monitoring Data

Actual Thai trucks were monitored on the BK-ERR highway, as mentioned in section (2) above. Because this highway is near Bangkok town, traffic is very heavy, particularly during the day when many small cars use it; a total of ninety hours of data was collected at night from 9: 30 p.m. to 6: 30 a.m. For simulating long-term monitoring truck data, the software was written by the author using MATLAB languages to calculation truck configuration.

A total of 10,621 trucks have been obtained from this study, as shown in Figure 5. Only those trucks that induced a total bridge strain of more than 40 micro strains were investigated, because a total strain signal of less than 40 micro strains was a small car or pick-up. From these test results, the trucks have been classified into seven types. The relative frequency of GVW for loaded truck and configuration of each truck type are presented in Figure 5 (a) and (b), respectively. For similarity to truck numbers as classified by Transportation Department of Thailand [14], the truck types monitored by this study were defined such as: 2-axle trucks (TR-02), 3-axle trucks (TR-05), 4-axle semi-trailers (TR-07), 5-axle semi-trailers (TR-09), 6-axle semi-trailers (TR-10), 5-axle trailers (TR-11), and 6-axle trailers (TR-12).

Figure 5 shows that most of the trucks on this highway are 2-axle trucks (TR-02, about 42%), 3-axle trucks (TR-05, about 27%), and 5-axle semi-trailers (TR-09, about 21%). There are few trucks for 4-axle semi-trailers (TR07, 2%), and 6-axle trailers (TR-12, 0.3%). For trucks 6-axle semi-trailers (TR-10), and 5-axle trailers (TR-11) are about 3% for each. It also can be observed that tuck TR-09 is more popular used than TR-10, while configuration of these trucks are different only rear axle group, two-axle group (tandem) for TR-09, and three-axle group for TR-10.



a). Locations of devices on bridge b). Cross section of bridge

Figure 5. Evaluation of truck weight

Figure 6(a) to (f) shows the relative frequency of GVW for each truck type that obtained in this study. Figure 6(a) shows the truck TR-02, which ranges between 8 tons and 19 tons; the lower GVW may indicate an empty truck and not include in this figure. The dividing line for loading condition is selected by judgment, GVW distribution at low peaks are assumed as empty trucks, and COV for loaded trucks is considered less than 0.3 [15]. Most of the GVW for TR-02 trucks ranged between 10 and 13 tons, and only few trucks, about 4%, had a GVW above 15 tons, which is the over legal limit load defined by the Transportation Department of Thailand [14].

Figure 6(b) shows the relative frequency of GVW for loaded trucks, TR-05, which ranges from 15 tons, light GVW trucks are not included in the graph. The maximum GVW is about 30 tons, while the GVW legal limit for this type of truck is 25 tons [14]. The monitoring data indicates that most trucks are under the legal load limit, only 4% above the legal limit.

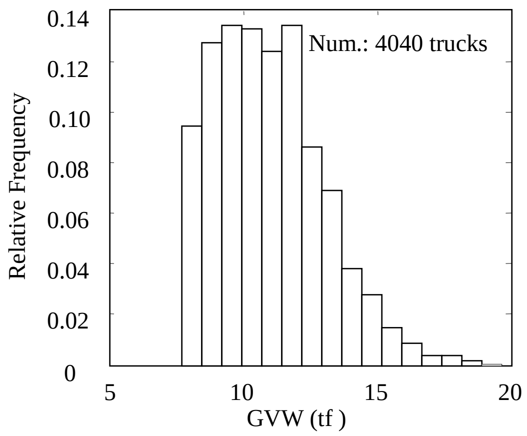
Figure 6(c) shows the relative frequency of GVW for the TR-07 trucks, which comprised only 2% of the total monitored data. This figure shows loaded trucks which GVW are more than 20 tons. The maximum GVW for the TR-07 group was about 33 tons. This truck type is not existed in the Transportation Department's list of legal trucks [14].

Figure 6(d) shows the relative frequency of GVW for the TR-09 group, and only loaded trucks are selected, which GVW are more than 25 tons. The maximum GVW for TR-09 is about 50 tons, while the legal GVW limit is 45 tons [14]. However, only a few trucks, less than 3% were above the legal weight limit.

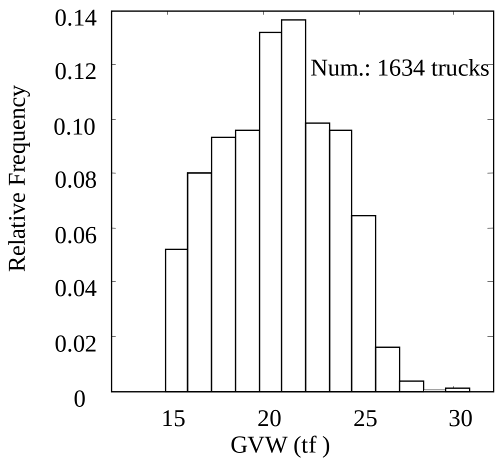
Figure 6(e) shows the relative frequency of GVW for the TR-10 trucks, and this figure includes only loaded trucks that GVW are more than 25 tons, and the maximum GVW of 58.1 tons. The legal GVW limit for this truck type is 50.5 tons [14]. The configuration of the TR-10 truck is different from the TR-09 truck only that trailing for TR-10 is three-axle group, while TR-09 is tandem.

Figure 6(f) shows the relative frequency of GVW for the TR-11 trucks, which GVW for loaded trucks are more than 30 tons. This truck type is a combination of a TR-05 truck and a trailer. The legal GVW limits for these truck types is 47 tons [14], while the maximum GVW values in this monitored data is up to 50 tones. However, less than 3% have a GVW exceeding the legal limit.

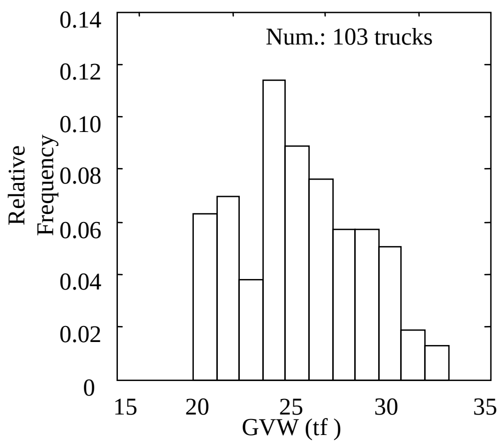
There are a few numbers for TR-12 trucks in this monitoring (only 0.3% of total monitored data). The loaded trucks have been selected as GVW higher than 30 tons, and only 7 loaded trucks can be observed. Therefore its data is not enough to present the graph of relative frequency of GVW. However, it can summary that the maximum GVW from monitored data is 54 tons, while the legal GVW limits is 53 tons [14].



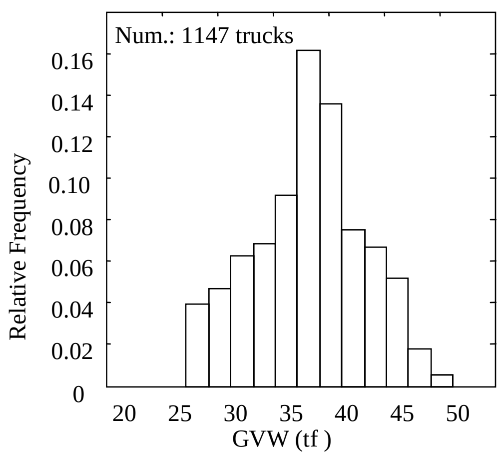
a). Relative frequency of GVW for TR-02



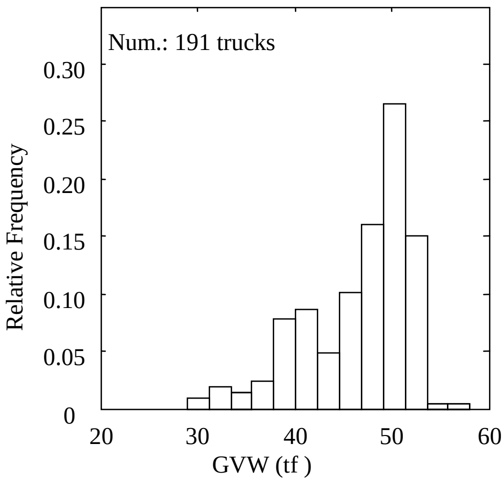
b). Relative frequency of GVW for TR-05

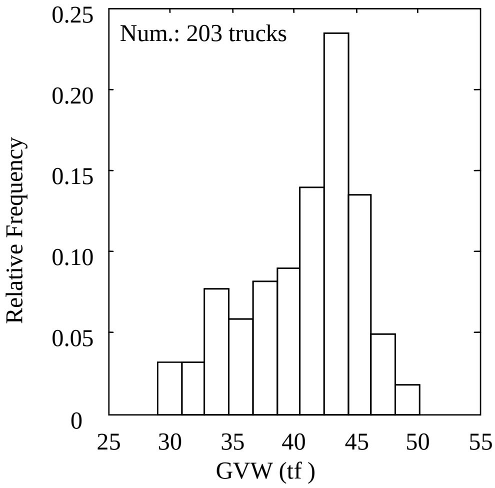


c). Relative frequency of GVW for TR-07



d). Relative frequency of GVW for TR-09





e). Relative frequency of GVW for TR-10 f). Relative frequency of GVW for TR-11

Figure 6**.** Relative frequency of GVW of trucks

The axle and axle group weights data of each truck are given in the Table 1, and axles spacing data are given in Table 2, as statistic values. Loading from closed spacing axles (spacing B, D, E Figure 5(b)) have been assumed as one axle group load (one point load), such as in Table 1 the axle-2 is single axle load for TR-02 and TR-07, and is axle group load for other truck types.

The mean value (MV), standard deviation (SD), and coefficient of variation (COV) for axle and axle group weights of trucks are given in Table 1. It seen that the MV of front axle weights (axle- 1) are ranged 3.36 tons to 4.88 tons, and SD are 0.8 to 1.11. The important trucks are TR-05 and TR-09, the MV of two axle group load (axle-2, axle-3) of these trucks are 14.26 tons to 17.84 tons, which SD is up to 4.06. It seen that Tr-05 and TR-09 are heavy truck loads popularly using in Thailand. For configuration of the TR-10 is similar to TR-09, it is different only that trailing which TR-10 is three-axle group (Figure 5(b)), while TR-09 is tandem. The MV of three-axle group of TR-10 is 23.96 tons, and SD is 3.91. TR-10 truck type is heaviest truck load. However, the small numbers of this truck type are found which it is only 3% of total truck data from this study. TR-011 and TR-12 trucks are trucks that combination of a TR-05 truck and trailers, their axle loads of these trucks are also similar to Tr-05 combination with trailers axle. The MV of the tandem axle weight 18.96 tons, and SD is 2.26, the MV of single axle weight of trailer is 9.06, and SD is 1.06 for TR-011. These truck types are also heavy truck load in Thailand that may generate more loads to bridge structures, especially for medium and long span bridges. In this monitoring, only little number of TR-12 has been found.

The median value (MD), standard deviation (SD), and coefficient of variation (COV) of axles spacing data of each truck type are given in Table 2. A is the spacing between first and second axles. The MD axle spacing A for TR-02 is 5.07 m with SD is 0.93. The spacing of TR-02 quite varies, due to that two axle truck may include four wheels and six wheel truck, however according to axle loads and GWV, this truck type is light weight truck in Thailand. The MD of axles spacing A and B for TR-11 and TR-12 are the similar to TR-05 with 4.12m and 1.3 m for A and B, respectively, because these trucks are TR-05 combination with trailers, and these axles spacing value are similar to that Thai truck data from factory [14]. The MV of axles spacing A, B, D for TR-07, TR-09 and TR-10 are also similar to each other which are about 3.75 m, 1.35 m, and 1.35m, respectively. These spacing values also are similar to data collected from factory [14]. It seen that only axle spacing, C value that is quite varied and differed between truck types.

Table 1. Axle/Axle Group Weights

Axle	Axle-Weight	TR-02	TR-05	TR-07	TR-09	TR-10	TR-11	TR-12
1	MV(tons)	3.36	4.30	3.78	4.79	5.62	4.63	4.88
	SD	0.88	1.00	0.84	1.04	1.06	1.11	1.04
	COV	0.26	0.24	0.22	0.22	0.22	0.24	0.21
2	MV(tons)	7.63	16.44	9.29	14.26	17.66	18.52	19.29
	SD	1.89	2.80	1.94	3.36	2.75	2.26	2.92
	COV	0.25	0.17	0.21	0.24	0.16	0.12	0.15
3	MV(tons)	-	-	12.77	17.84	23.96	8.88	9.45
	SD	-	-	3.08	4.06	3.51	1.92	3.62
	COV	-	-	0.24	0.23	0.15	0.22	0.38
4	MV(tons)	-	-	-	-		9.06	14.23
	SD	-	-	-	-		1.87	4.93
	COV	-	-	-	-		0.21	0.35
GVW-max(tons)		**19.6**	**31.1**	**33.7**	**49.7**	**57.9**	**50.0**	**53.6**
GVW-Legal limit (t)		**15.0**	**25.0**	**-**	**45.0**	**50.5**	**47.0**	**53.0**

Table 2. Axle Configuration

Truck	Spacing	TR-02	TR-05	TR-07	TR-09	TR-10	TR-11	TR-12
A	MD(m)	5.07	4.12	3.75	3.36	3.37	4.12	4.12
	SD	0.93	0.49	0.88	0.24	0.25	0.32	0.24
	COV	0.19	0.12	0.22	0.07	0.08	0.08	0.06
B	MD(m)	-	1.30	1.35	1.30	1.30	1.30	1.30
	SD	-	0.08	0.10	0.05	0.07	0.07	0.04
	COV	-	0.06	0.07	0.04	0.05	0.05	0.03
C	MD(m)	-	-	8.07	7.20	6.26	4.38	4.60
	SD	-	-	1.41	1.28	1.26	0.46	0.72
	COV	-	-	0.18	0.19	0.22	0.01	0.11
D	MD(m)	-	-	-	1.35	1.35	-	1.34
	SD	-	-	-	0.06	0.07	-	0.05
	COV	-	-	-	0.05	0.05	-	0.03
	MD(m)	-	-	-	-	1.35	-	-

E	SD	-	-	-	-	0.07	-	-
	COV	-	-	-	-	0.05	-	-
F	MD(m)	-	-	-	-	-	4.40	3.35
	SD	-	-	-	-	-	0.34	0.35
	COV	-	-	-	-	-	0.08	0.10

Discussion Truck Data Obtained From Monitoring System

Most of trucks from this monitoring loaded under legal limit. Each truck type has found only about 3% loaded higher than legal limit. Frequency of the GVW, for tow axles truck (TR-02) most of loaded trucks are about 10 tons, TR-05 (about 21 tons), TR-07 (about 24 tons), TR-09 (about 36 tons), TR-10 (about 50 tons), TR-11 (about 44 tons), TR-12 (about 50 tons). All truck are heavy trucks loads, accept TR-02 group. Few overloaded trucks were seen in this monitored data, likely due to that there is weight control station on this highway. Other Thai highways without weight control stations may see more overloaded trucks.

From the above truck data, the configurations (axle spacings) of trucks are varied depend on truck type, which can be observed from the SD of axle spacing. SD of axle spacing for TR-02 is 0.93, which indicates that axle spacing data quite large varies between maximum and minimum values (varying from 3 m to 6 m). This due to that of TR-02 group consists of four wheels (single wheel at second axle) and six wheels (double wheels at second axle). For TR-05, and leader trucks for TR-11 and TR-12 trucks are similar configuration, MD of first and second axles spacing (A and B) are 4.12 m and 1.3 m, and SD are 0.49 and 0.07 respectively. The varying of first axle spacing of TR-05 is between 3.3 m to 5 m; however most data are about 4.12 m. This data are agreed with data from factory in Thailand [4]. The SD of C, axle spacing between heading and trailing of semi-trailer truck types, TR-07, TR-09, and TR-10 are higher than one, due to that the axle spacing for theses truck groups are much varied between 3.5 m to 9 m. This is due to the configuration of semi-trailer groups consist of different length, and there are no regulations for axle spacing of trucks in Thailand. However, the individual axle spacing in axle groups for these truck types are similar, which D value is about 1.35 m.

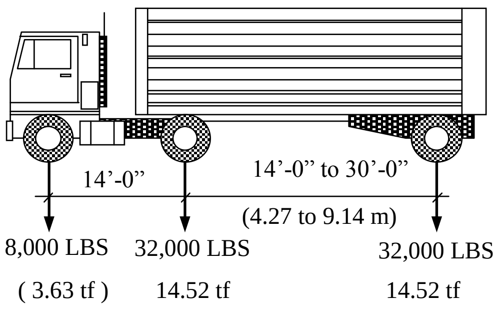


Figure 7. HS20-44 (AASHTO) truck

To investigate over loaded trucks, the heaviest truck in each truck type from the monitored data was compared to the HS20-44 standard design truck in the AASHTO code. HS20-44 encompasses truck loading and lane loading, for bridges with spans shorter than 35m, only truck loading is considered because it induces a greater load on such bridges than lane loading [5]. Small and medium size bridges in Thailand have been designed according to the HS20-44 design truck as shown in Figure 7. The monitored trucks (Thai trucks) in from this study shown in Tables 1 and 2 above have axle configurations that do not differ much from that of the HS20-44 design truck, which the axle spacing varying between 4.1m and 9 m (from center to center for axle group). However, the axle weight and GVW of the heaviest loaded truck in each monitored truck group, except the TR-02 group, are higher than that of the HS20-44 truck.

Table 3 shows the axle weights of the heaviest truck for each type from monitored data and to axle load of HS20-44 design truck. The individual axle weight in axle group is assumed as equal load. The GVW of each heaviest truck type is a sum of axle weights. It is seen that only the TR-02 truck has a GVW that is much lower than that of the HS20-44 design truck. The GVW of heaviest TR-10 truck is almost twice that of the HS20-44 design truck. Steering axle weights for all heaviest trucks are higher than 3.63 tons, which those of HS20-44. Weights of individual axles are less than 14.52 tons; however, axle group weights of heaviest trucks (sum of individual axle weight in axle group) for each truck type are higher than second and third axle of the HS20-44 truck. For example, the heaviest for two-axle group is up to 26 tons, and the heaviest for three-axle group is up to 30 tons, while the axle load of the standard design truck is 14.52 tons.

Table 3. Axle Weights of Heaviest Truck From Monitoring Data (tons)

Axle	HS20-44	TR-02	TR-05	TR-07	TR-09	TR-10	TR-11	TR-12
1	3.63	4.3	4.7	4.0	5.1	4.7	4.5	5.3
2	14.52	15.3	26.2	11.1	20.0	23.2	22.8	18.4
3	14.52	-	-	18.6	24.6	30.0	11.1	13.7
4	-	-	-	-	-	-	11.6	16.2
GVW	**32.66**	**19.6**	**31.1**	**33.7**	**49.7**	**57.9**	**50.0**	**53.6**

These heaviest Thai trucks from monitored data are also compared to the HS20-44 truck by computing the maximum bending moment for simply span bridges with a length between 5 m and 35 m. It is found that the effects of the heaviest Thai truck types—TR-05, TR-09, TR-10, TR-11, and TR-12—are exceeded by those of the HS20-44 truck. For spans less than 15 m in length, the maximum moment is induced by the trucks in the TR-05 and TR-10 groups, and this maximum moment is about 48% greater than that of the HS20-44 truck. On longer spans, the maximum moment is induced by the trucks in the TR-10 and TR-11 groups. This moment is about 40% greater than that of the HS20-44 truck.

Conclusions

In this study, actual truck data at Bangkok, Thailand have been monitored using system innovated by author which based on the BWIM system. The system is uncomplicated and inexpensive, no equipment exposed to roadway leading to easy to install and maintain.

The Bangkok Eastern Ring Road (BK-ERR) in Thailand was selected for monitoring actual truck configurations and loads. The results of this test can classify the actual trucks into seven types. The configurations of trucks can be grouped such as two axle truck, three-axle truck, semi-trailer truck, and full trailer truck. The data of GVW, axle and axle group weights and axle configurations of Thai truck are presented. The axle spacing from monitoring data agreed with data from truck factory. Even though there are weight control stations on tested highway, the over truck load still can be observed.

From nominal analysis of short- to medium-span bridge, all of the heaviest of the monitored trucks (or actual Thai trucks) generate loads on bridges that are higher than that of the HS20-44 design truck. The heaviest truck load can reach as high as 48% above that of the HS20-44 design truck. The effects of truck loads on bridges are produced not only by the axle weight but also the axle spacing.

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