CHAPTER VII

Bridge Weigh-In-Motion Application

7.1 General

Bridge Weigh-In-Motion (B-WIM) is the process by which axle and gross weights of trucks travelling at highway speeds can be determined from instrumented bridges. The B-WIM data can be used for any applications such as pre-selection of overweight trucks for static weighing, pavement design/assessment or bridge design/assessment. In this chapter, the application of the B-WIM to monitor the actual truck weights in the road network is conducted. The information of many trucks in the normal traffic condition is obtained. Bridge live load models from design code such as HS20-44 and design Thai truck are compared with this measured truck database from B-WIM. This is a first study in the country which the existing bridge design live load is evaluated and discussed based on actual acquired truck load data using statistical and probabilistic approach.

7.2 Bridge Weigh-In-Motion System

According to the studies of the axle loads identification using the small-scale and full-scale tests, they clearly show that the test system and the axle weight estimation methods can be used as B-WIM system in the normal traffic condition with acceptable accuracy level of the WIM system of ASTM type-III. Therefore, the instrumented bridge system as previously outlined for field investigation is installed for B-WIM application. For the purpose of the axle weight identification, dynamic strain responses induced by the passing of only one truck are measured by the data acquisition system. The truck speed and axle spacing are determined from the axle detector signals. To do so, two axle detectors are mounted at the entry and exit points of the bridge span and their measured signals are also recorded by the data acquisition system. After processing these signals, the truck speed and axle spacing of can be obtained. In addition, the travelling path of the truck which may influence an accuracy of axle weight estimation is monitored. A CCTV camera is installed on the post beside the bridge to observe the truck travelling path as well as the traffic condition on the bridge deck.

Since the obtained results from experimental and field investigations indicate that the vehicle weight estimations using the Method II is slightly better than those using the Method I. Therefore, in this chapter, the Method II is chosen to estimate the axle weights of the passing trucks. For convenience, the regularization parameter for the Method II is set to be 10.0 for all trucks. Since the second and third axles are very close and are difficult to be separately identified as described in the previous chapter, they are modeled by an equivalent single rear axle acting through their center and fixed at a distance of axle spacing of 1.30 m for all trucks. Therefore, the middle and rear axle weight is assumed to be the same value and equal to a half weight of the equivalent single rear axle. Based on this procedure, the parameters of the 10-wheel truck, such as the front and rear axle weights, the gross truck weight, the axle spacing, the truck speed and the travelling path, are calculated. Figure 7.1 shows the typical measured bending moments and axle detector signals. The typical axle load identification result is shown in Figure 7.2. Figure 7.3 shows the pictures of trucks which are extracted from the video record using CCTV camera. Table 7.1 lists the example of truck information databases which is recorded from B-WIM system.

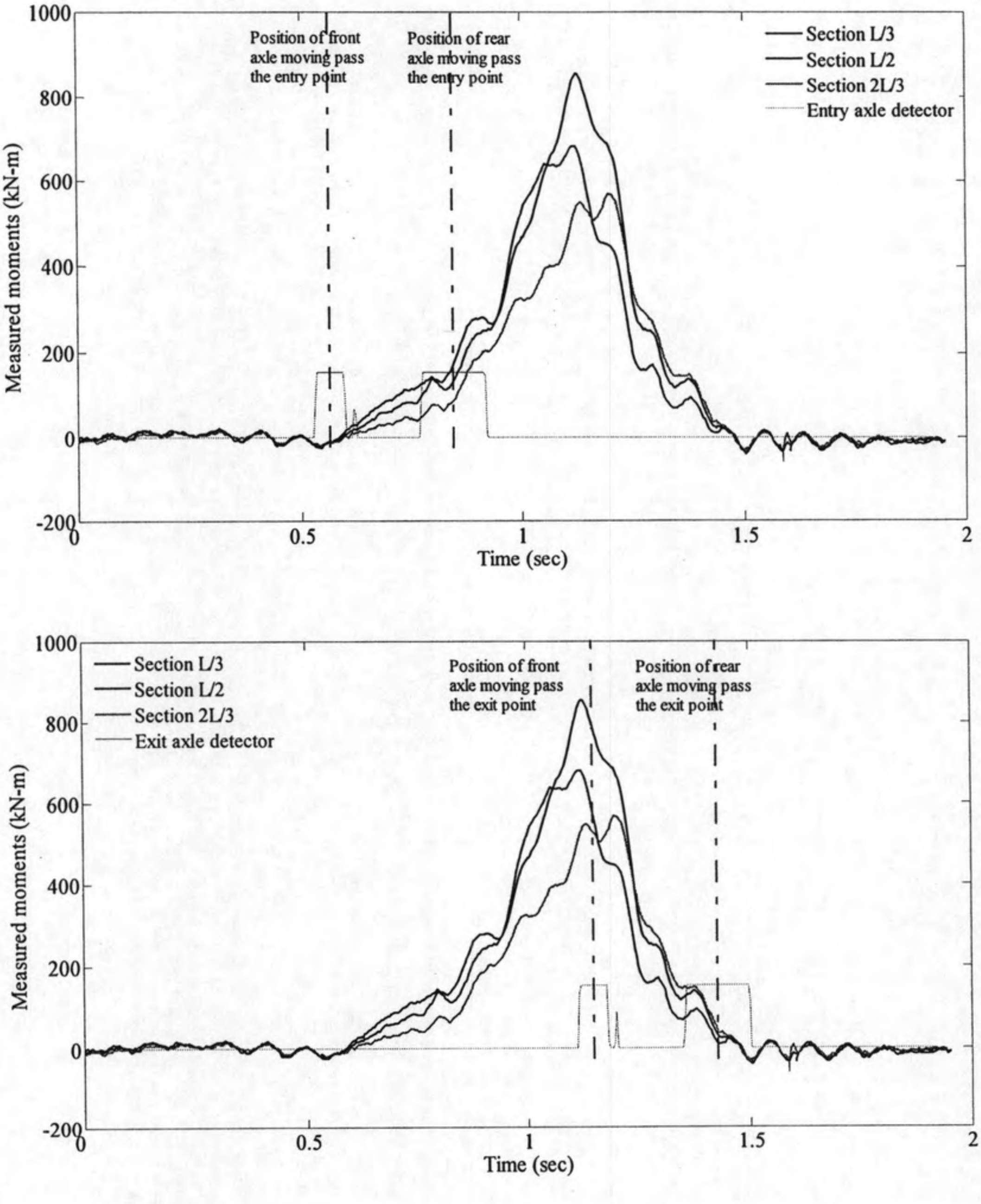


Figure 7.1 Typical measured bending moments and axle detector signals

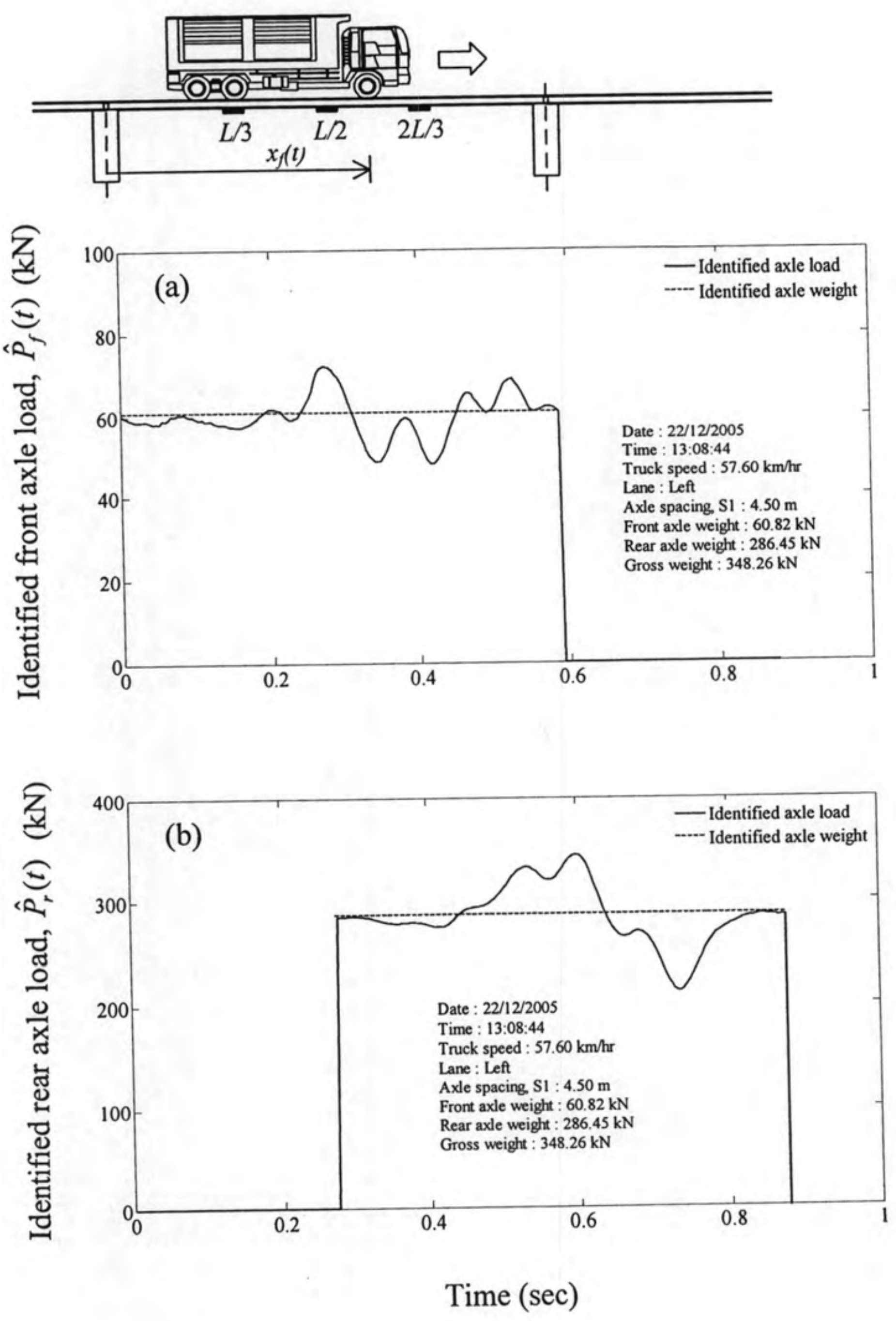
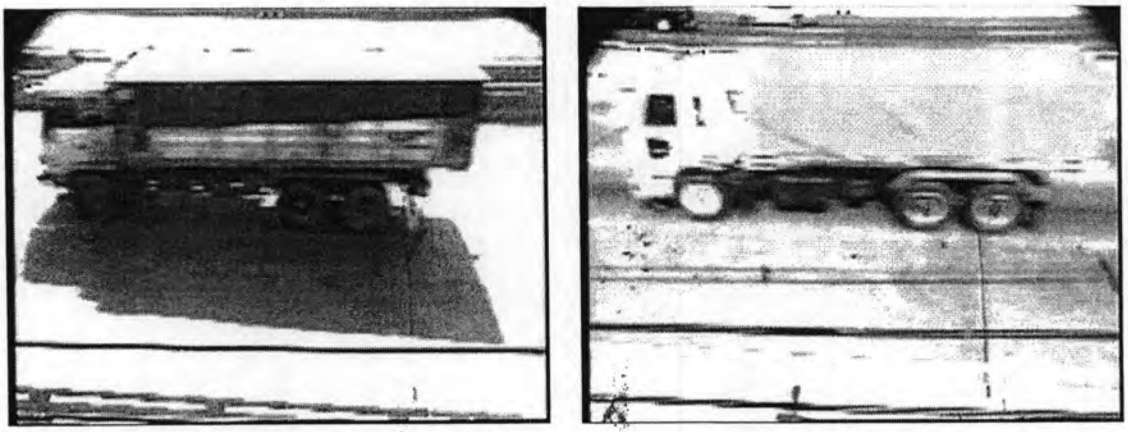
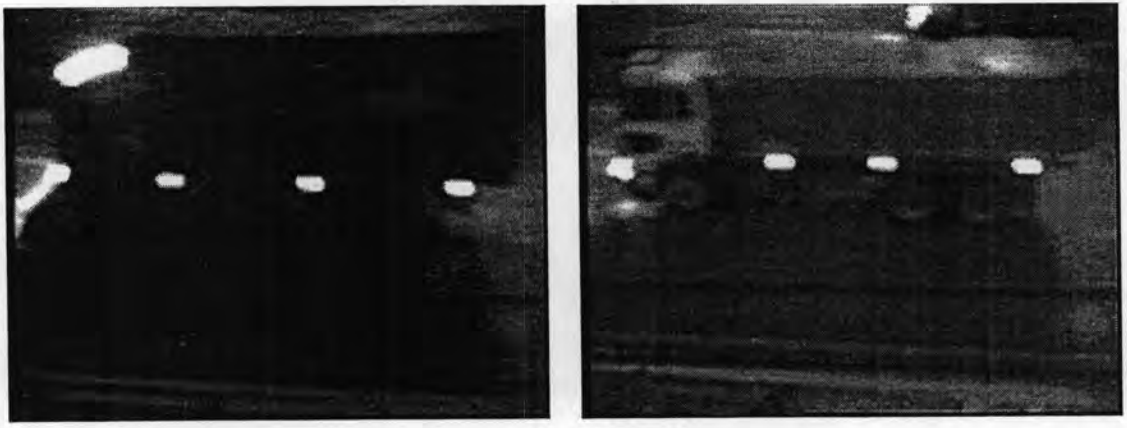


Figure 7.2 Typical axle loads identification from B-WIM system



(a) Day time



(b) Night time

Figure 7.3 Photographs of truck which are recorded from CCTV camera

Table 7.1 Example of B-WIM databases

NO	Date	Time	Spacing S1 (m)	Speed (km/hr)	Lane	Nf (kN)	Nr (kN)	Nt (kN)
⋮								⋮
4406	2005_12_22	12_31_10	4.86	32.9	Middle	41.5	184.4	225.8
4407	2005_12_22	12_36_26	4.52	45.3	Middle	59.4	168.3	227.7
4408	2005_12_22	12_36_26	4.76	45.3	Middle	47.8	170.0	217.8
4409	2005_12_22	12_53_34	4.69	54.7	Middle	36.8	199.0	235.8
4410	2005_12_22	12_56_12	4.56	42.0	Middle	56.6	158.7	215.4
4411	2005_12_22	13_06_44	4.59	55.7	Right	68.8	227.8	296.6
4412	2005_12_22	13_08_04	4.50	57.6	Middle	60.8	285.5	348.3
4413	2005_12_22	13_34_32	3.89	60.8	Middle	32.9	109.0	142.0
4414	2005_12_22	13_38_28	4.00	42.4	Middle	76.5	244.2	320.7
4415	2005_12_22	13_42_26	4.74	49.7	Right	54.0	255.1	309.1
⋮								⋮

7.3 Bridge Weigh-In-Motion Records

The 10-wheel trucks with 3 axles are widely used in Thailand and the overweight truck problems are often detected in the highway network. The truck records are obtained from the existing bridge with B-WIM system as described in the previous section. The records are collected during 19/07/2005 to 30/12/2005 and cover about 5,049 heavy trucks (only 10-wheel trucks which appeared to be heavily loaded were measured and included in the records).

The parameters of the 10-wheel trucks, such as the front, middle and rear axle weight, truck gross weight, axle spacing, truck speed and the travelling path, are considered. Figure 7.4 provides the graphical sketches of the 10-wheel truck. The criteria for considered truck parameters are listed in Table 7.2. The limitations of parameters refer to the axle weight and configuration of standard 10-wheel trucks which usually being used in Thailand.

Table 7.2 Criteria for truck parameters

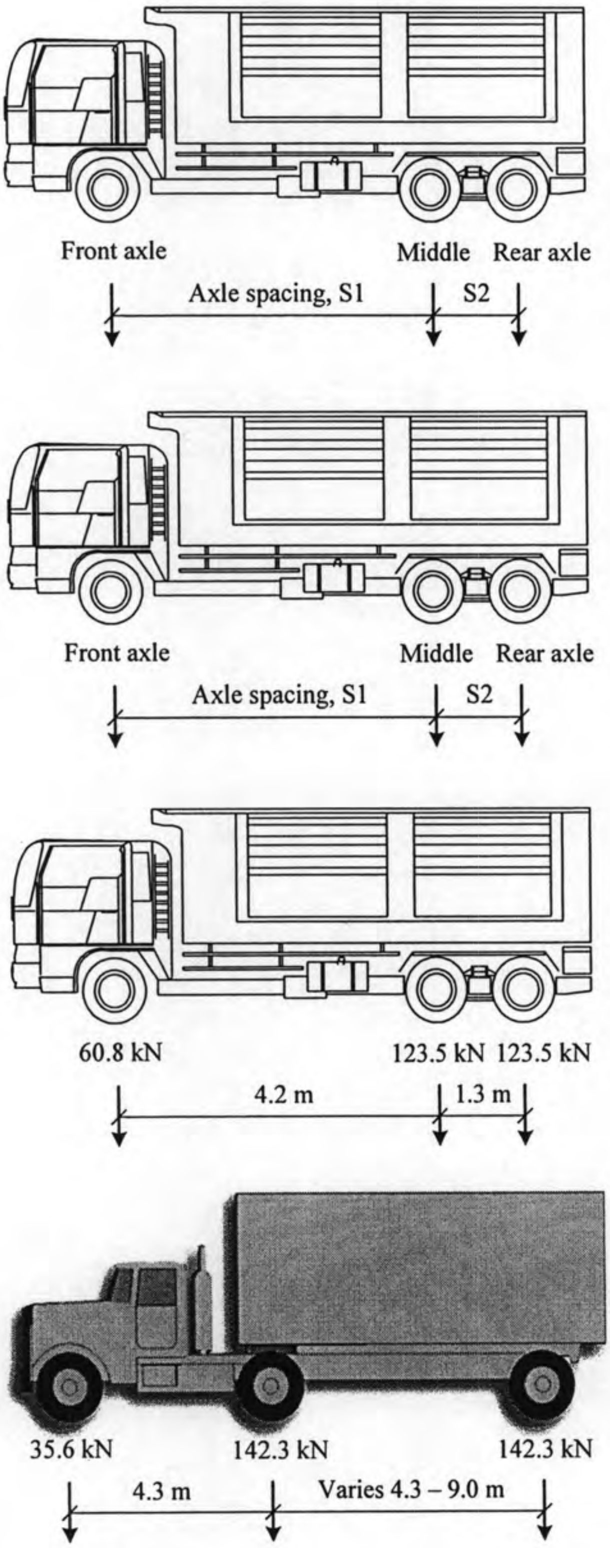
Parameter	Criteria
Front axle weight	> 19.6 kN (2.00 T)
Middle and rear axle weight	> 78.4 kN (8.00 T)
Truck gross weight	> 98.0 kN (10.00 T)
Axle spacing, S1	3.00 – 5.00 m
Axle spacing, S2	1.30 m
Ratio of front axle weight/gross weight	> 0.12

7.3.1 Thailand Legal Limitations and Design Truck Loads

The Thailand's legal weight limits of a 10-wheel truck are regulated by Department of Highways. The legal weight limits allow tandem axle weight to be not more than 196 kN (20.0 T) and the truck gross weight to be not more than 245 kN (25.0 T). However, it is found that the overweight problem of 10-wheel trucks in Thailand is often detected. In the bridge design and evaluation specification, the load models of design Thai truck and AASHTO specification are employed. The design Thai truck is a 307.7 kN single truck with the front, middle and rear axles which represents the 10-wheel truck being used in Thailand. While, the AASHTO load models consists of a single design truck called truck loading type HS20-44 and a distributed lane loading. However, for the short span bridges having span length of less than 30 m, the truck loading HS20-44 usually governs the design of the bridge (Nowak and Szerszen, 1998). The sketches of each load model are graphically shown in Figure 7.4.

7.3.2 Axle Weights

The axle weights of 10-wheel trucks determined by the B-WIM system are composed of the front, middle and rear axle weights. In this study, the middle and rear axle weights are assumed to be the same value. This is because the middle and rear axles are a tandem axle with closely space axles. A gross weight of the truck is a total truck weight and is equal to summation of front, middle and rear axle weights. Based on the B-WIM records, the statistical results are presented by the weight histograms as shown in Figure 7.5(a) to 7.5(c). It is found that the mean of the middle and rear axle weights and the gross truck weight are 172.31 kN and 217.28 kN, respectively. These mean axle weight values are below the legal weight limits. However, there are 901 trucks (17.85%) that exceed the legal weight limit for tandem axle (weight more than 196 kN) and are 858 trucks (16.99%) that exceed the legal weight limit for gross weight (weight more than 245 kN). These B-WIM records clearly indicate that there are a significant number (about 15%) of overloaded trucks moving in the highway network. Moreover, the maximum gross weight of the trucks obtained from B-WIM records is approximately 420.75 kN which is 175.75 kN heavier than the legal weight limit. (1.72 times of the legal limit). It should be noted that these heavy trucks produce large impact loadings that may cause damage to the pavement and the bridge structure.



B-WIM database

Front axle wt. > 19.6 kN
Middle and rear axle wt. > 78.4 kN
Gross wt. > 98.0 kN
Axle spacing, S1 = 3.00-5.00 m
Axle spacing, S2 = 1.30 m
Ratio of front/gross > 0.12 m

Thailand legal limitations

Middle + rear axle wt. < 196 kN
Gross wt. < 245 kN

Design Thai truck

Front axle wt. = 60.8 kN
Middle and rear axle wt. = 123.5 kN
Gross wt. = 307.7 kN
Axle spacing, S1 = 4.2 m
Axle spacing, S2 = 1.30 m

AASHTO HS20-44

Front axle wt. = 35.6 kN
Middle and rear axle wt. = 142.3 kN
Gross wt. = 320.1 kN
Axle spacing, S1 = 4.3 m
Axle spacing, S2 = 4.3-9.0 m

Figure 7.4 Sketches of truck load models

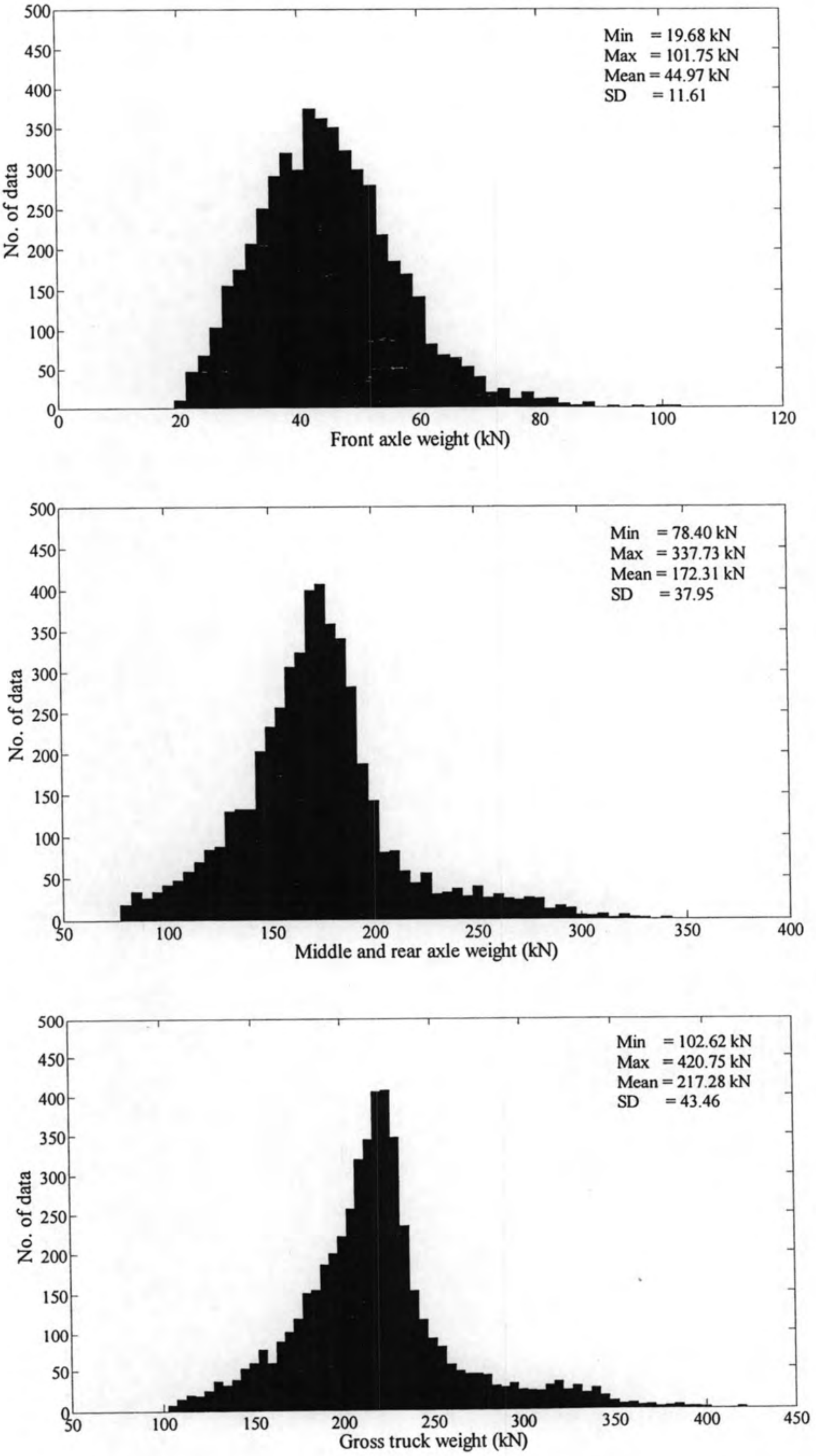


Figure 7.5 Histogram of axle weights (a) front axle (b) middle and rear axle (c) gross weight

7.3.3 Axle Spacing

The axle spacings of 10-wheel trucks from B-WIM records are determined by the axle detector signals as described in previous section. Although the truck has 3 axles, the distance between 2 closely space axles cannot be measured accurately because of the limitation of axle detectors. However, it is observed from the most widely used 10-wheel trucks in Thailand that the distance of axle spacing of tandem axle does not much vary and it may assume to be fixed at a distance of 1.30 m for all trucks. The statistical results of measured axle spacing (S1) are presented by a spacing histogram as shown in Figure 7.6. The results indicate that the axle spacing (S1) varies about 3.01 m to 4.84 m and the mean value is 3.78 m. Comparing with the design Thai truck, it is found that the average measured axle spacing is significantly less than the standard Thai truck axle spacing (4.20 m). These results indicate that the bridge moments induced by the actual trucks can significantly greater than that computed from the design truck load. Consequently, the bridge design using an existing design Thai truck may not be conservative.

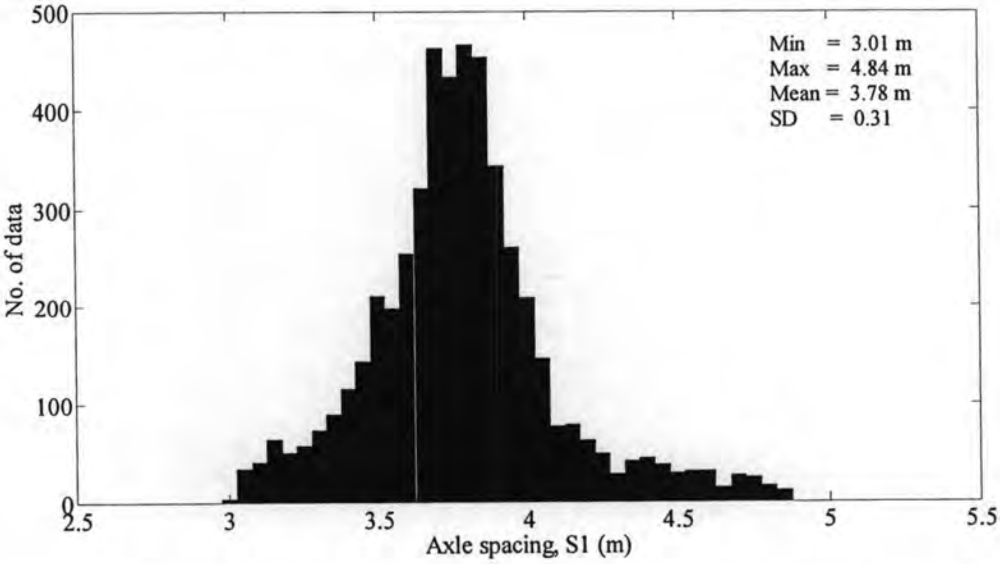


Figure 7.6 Histogram of axle spacing (S1) from B-WIM database

7.3.4 Truck Speed and Travelling Paths

The truck speeds and the travelling paths are the other important parameters of truck loading characteristics. The obtained truck speed distribution is presented by the speed histogram as shown in Figure 7.7. It is found from the figure that the truck speed varies between 18 – 85 km/hr in the normal traffic. Figure 7.8 plots the relationship between truck gross weights and measured truck speeds. Although, in general, the heavier trucks should travel with slower speeds. It is observed from the records that the truck speeds are not clearly affected by the gross weights. The speed distribution also shows that most of the trucks are moving with the moderate speed between 30-70 km/hr. This speed range is found to be normal for the vehicles in the considered highway.

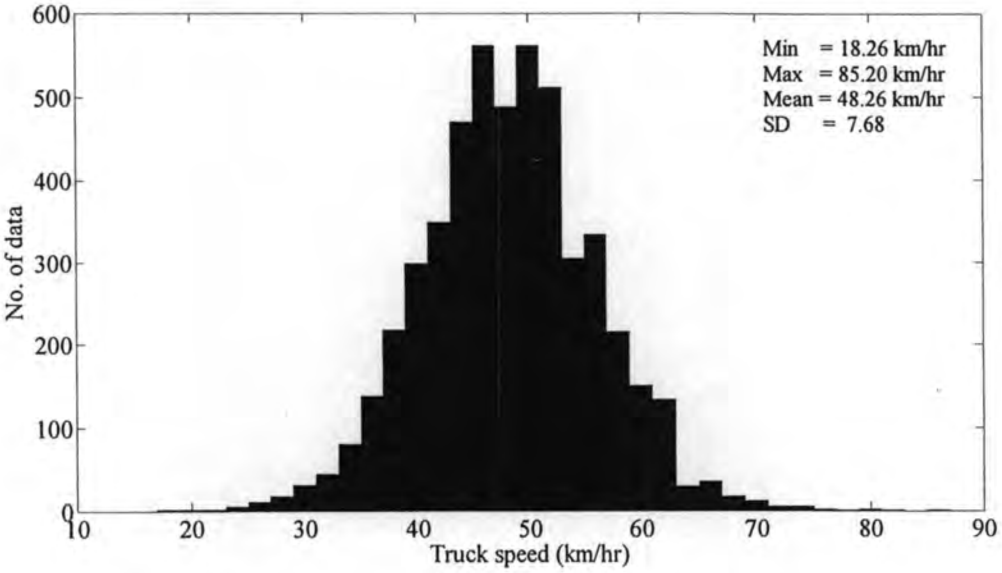


Figure 7.7 Histogram of measured truck speed from B-WIM database

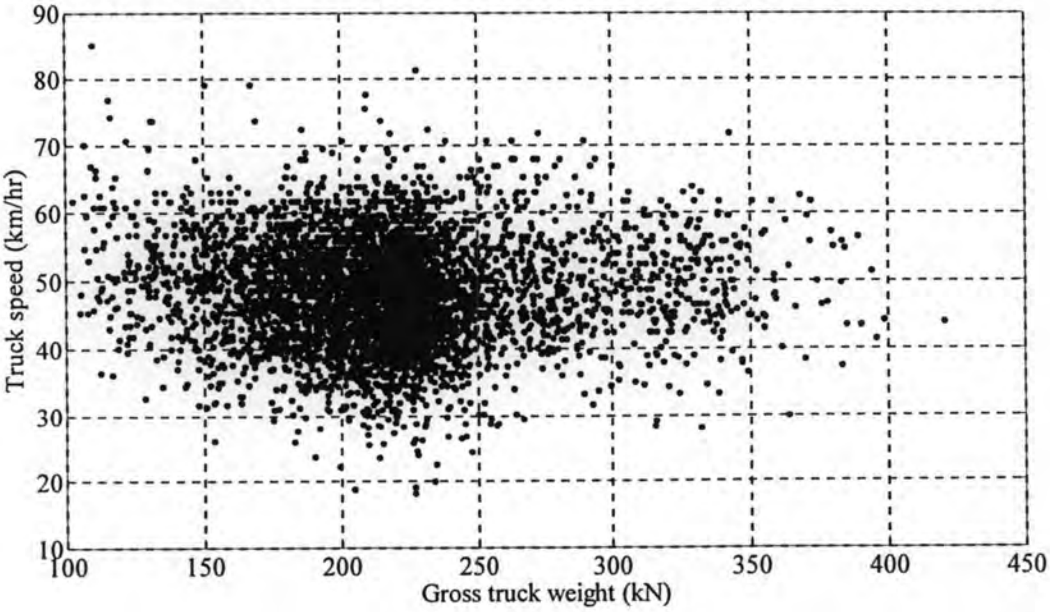


Figure 7.8 Relationship between truck gross weights and measured truck speeds

The number of trucks moving in each travelling paths are listed in Table 7.3. It is observed that more than 87% of trucks traveled on the middle lane. The average truck speed in the left lane is slightly less than the other lanes. It is also observed that the average gross truck weight in the right lane is slightly higher than the other lanes.

Table 7.3 Behavior of moving truck on the various travelling paths

Travelling paths	No. of data	% of data	Avr. speed	Avr. gross wt.
Left	312	6.2%	44.3 km/hr	21.54 T
Middle	4440	87.9%	48.5 km/hr	22.07 T
Right	297	5.9%	48.7 km/hr	24.32 T

7.4 Truck Load Models

Load models are an important part of the design code. The major load components of a bridge design are dead load, live load, dynamic or impact load, environmental loads (temperature, wind earthquake), and other loads (collision, emergency braking). The design code specifies design loads, load combinations, and load factors. In the AASHTO specification, the bridge design equation is

$$\phi R_n > \sum \gamma_i X_i \qquad (7.1)$$

where R_n = nominal (design) resistance

ϕ = resistance factor

X_i = nominal (design) load component i

γ_i = load factor i

The basic load combination for a bridge design is a simultaneous occurrence of dead load, live load and dynamic load. In general, the basic bridge design formula can be expressed as

$$\phi R > \gamma_D D + \gamma_L (1+I) L \qquad (7.2)$$

where D = dead load

L = live load or truck load

I = impact factor

γ_D, γ_L = dead load and live load factor

For bridge design specification in Thailand, γ_D, γ_L = 1.3 and 2.17 respectively, Eq. (7.2) can be written as

$$\phi R > 1.3D + 2.17(1+I)L \tag{7.3}$$

Dead load (D) is the weight of structural and nonstructural members and is calculated by using specified densities of material and geometry of members. Impact factor (*I*) is specified by empirical formula with respect to bridge span length. The live load model (*L*) that consists of a single design vehicle is called a truck loading and another distributed load is called a lane load which is not governed for the short span bridge design. For a single vehicle load, two variables involved are concentrated loads and spacing between axle groups. The live load models are made for a possible heaviest vehicle in the life time of a bridge structure which covers a range of forces produced by vehicles moving on the bridge. This kind of load model can induce effects in a bridge structure in the same manner as the general traffic. However, the live load parameters depend on the configuration of a real vehicle and there may be a change in the vehicle configuration such as axle weight and gross weight by the legal regulation in the future. In this study, the comparison of a truck survey from B-WIM and load model for the bridge design specification in Thailand are considered. The live load factor in the design code is compared by using the statistical method. The extrapolation approach using the cumulative distribution function (CDFs) proposed by Nowak (1990) is adopted to obtain extreme design forces for comparing load models. This method is widely used and provides an effective way to obtain the maximum value of related parameters. The live load factor and live load models used in the bridge design in Thailand are discussed.

7.4.1 Cumulative Distribution Function (CDFs)

The obtained truck records including truck configuration (axle spacing) and weights (axle weight and gross weight) are considered. For each passing truck, bending moments and shear forces are calculated for a wide range of span lengths of simply supported bridges. Since, the previous research (Nowak, 1994) indicates that one truck governs the bridge design for span lengths shorter than 30-40 m. In this study, the short span bridges with 5-30 m span lengths are concerned and therefore only the truck load model is considered. The moments and shears from the bridge design code are calculated in term of the standard design Thai truck and HS20-44, whichever govern as shown in Figure 7.4. However, the overloaded truck factor of 1.3 as commonly used in Thailand is applied to the HS20-44. The bridge moment and shear ratios of the surveyed truck database with the design Thai truck and HS20-44 is considered. The cumulative distribution functions (CDFs) approach is adopted. Figure 7.9 and 7.10 show the plot of CDFs on the normal probability paper. The vertical scale in figures, z is

$$z = \phi^{-1}\left[F(x)\right] \tag{7.4}$$

where x = bending moment or shear force

$F(x)$ = CDFs of the moment and shear

ϕ^{-1} = inverse of the standard normal distribution function

While the horizontal scale is the bridge moment and shear ratios of the surveyed truck database with the design Thai truck and HS20-44 loads.

7.4.2 Maximum Truck Moments and Shears

The maximum truck moments and shears for various time periods are determined by extrapolation approach. The employed extrapolations are also shown in Figures 7.9 and 7.10. In the general design code, the average life time for a bridge is about 75 years. Therefore, this time period is used as the basis for the calculation of loads. Using the available data, a statistical model is developed for the mean maximum of 75 years moments and shears by extrapolation of truck survey data. Let N be the total number of trucks in time period T, it is assumed that the average daily truck traffic (ADTT) vary in the range 1,000-5,000 trucks per day with growth rate 2% and maximum ADTT less than 10,000 trucks per day. This will result in the number of trucks N for a considered time periods from 1-75 years and the probability level corresponding to N is $1/N$, which corresponds to the inverse normal distribution values, z, as listed in Table 7.4. Consequently, the mean maximum moments and shears of the bridges for various time periods (T) can be determined from the extrapolation distributions of CDFs as shown in Figures 7.9 and 7.10.

Table 7.4 Number of trucks, as time period and inverse normal z for various ADTT

Time period (T)	ADTT 1000 truck/day (2% traffic growth)		ADTT 2500 truck/day (2% traffic growth)		ADTT 5000 truck/day (2% traffic growth)	
	Truck Volume	z	Truck Volume	z	Truck Volume	z
1 year	365,000	4.55	912,500	4.73	1,825,000	4.87
10 years	3,978,500	5.03	9,946,250	5.20	19,892,500	5.33
25 years	11,315,000	5.22	28,287,500	5.39	56,575,000	5.51
50 years	27,192,500	5.38	67,981,250	5.54	135,962,500	5.66
75 years	47,632,500	5.48	119,081,250	5.64	227,212,500	5.75

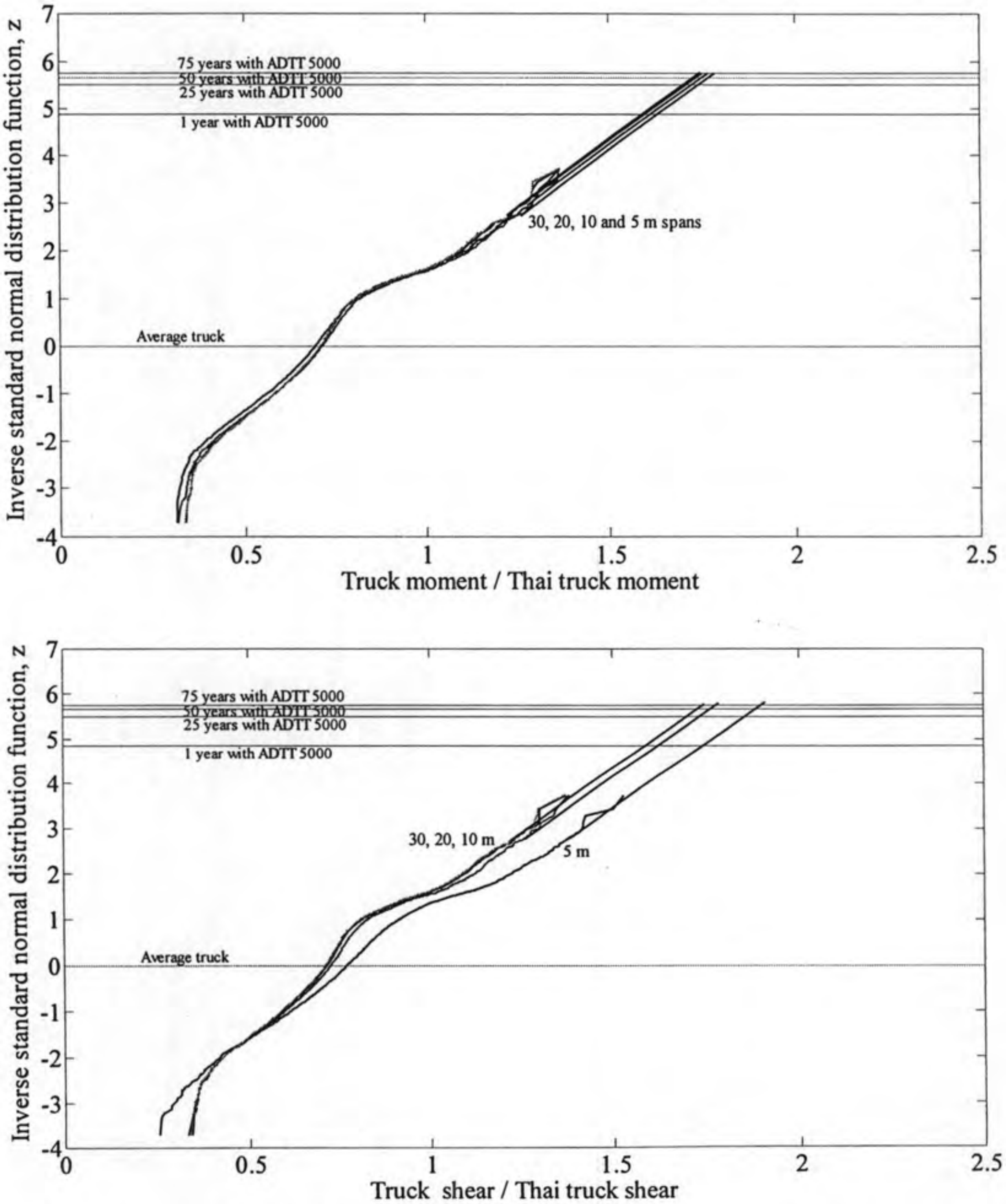


Figure 7.9 Cumulative distribution function for (a) moment and (b) shear due to surveyed trucks with respect to design Thai truck

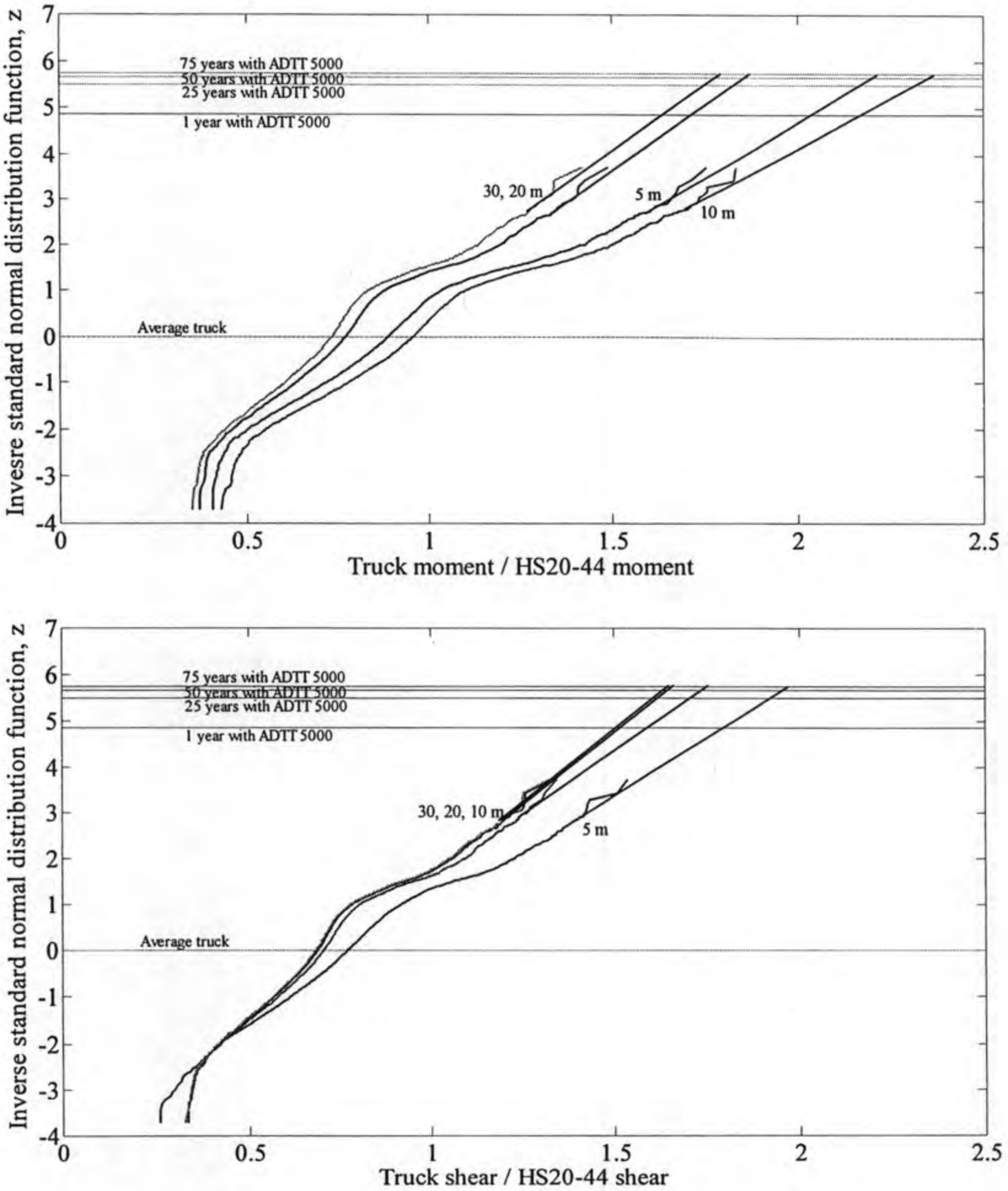


Figure 7.10 Cumulative distribution function for (a) moment and (b) shear due to surveyed trucks with respect to HS20-44

From Figures 7.9 and 7.10, the mean (average) values of the moment and shear ratios can be read directly from graphs, at the intersection of the CDFs with level 0 on the vertical scales. They are about 0.60-0.70 and 0.75-1.00 of the design Thai truck and HS20-44 moments, respectively. These results indicate that the effects of moments from the design Thai truck model for various span lengths are higher than the effects from HS20-44. For shears, the values are about 0.70-0.80 for both design Thai truck and HS20-44. The results indicate that the effects of shear from the design Thai truck model for various span lengths are close to the effects from HS20-44. For maximum effects from the surveyed truck data (5,049 trucks), it is found that the maximum truck moment ratios are 1.40 and 1.40 – 1.80 for the design Thai truck and HS20-44, respectively. For shears, the maximum values of about 1.40-1.55 and 1.30-1.55 are obtained for the design Thai truck and HS20-44, respectively. It is observed that the effects of truck configurations on the bridge moment and shear ratios are higher for the HS20-44. It is also observed that the maximum moment induced from actual truck data are much higher than those computed from both the design Thai truck and HS20-44. However, they are still not higher than the live load factor of design code (LL factor = 2.17).

The maximum bridge moments and shears for any time periods (T) are linearly extrapolated from CDFs as shown in Figure 7.9 and 7.10. For example, when $T = 75$ years with ADTT 5,000 trucks/day and a 2% traffic growth rate per year, this will results in 227,212,500 trucks and the probability level corresponding to this truck volume is 1/227,212,500, which corresponds to $z = 5.75$. As the result, the bridge moment and shear ratios of the actual trucks to the design Thai truck or HS20-44 can be calculated from the intersection of the CDFs to the values on the horizontal scale.

In this study, the only time period (T) of 75 years has been considered. The results are presented in Figure 7.11 to 7.12, for design Thai truck and HS20-44 moments (and shears) with various ADTTs, respectively. Comparing with the design Thai truck load model, the obtained results show that the ratios of mean maximum values of the short span bridge with ADTT 5000 trucks per day and a traffic growth rate of 2% per year are approximately 1.86 times of moments for a 10 m span length and 2.02 times of shears for a 5 m span length, respectively. The results show that the values are lower than the live load factor of 2.17 as recommended by the bridge design code. These indicate that the design Thai truck model with the live load factor of 2.17 has adequate safety level for design life time 75 years based on obtained B-WIM data. While, comparing with HS20-44, it is found that the ratios of mean maximum values of the short span bridge with ADTT 5000 trucks per day and a growth rate 2% per year are approximately 2.51 times of moments for a 7.5 m span length and 2.01 times of shears for a 5 m span length, respectively. The results show that the values are higher than the live load factor of 2.17 as recommended by the bridge design code. The results indicate that the HS20-44 model with live load factor of 2.17 has inadequate safety level for a design life time of 75 years based on obtained B-WIM data. However, in Thailand practice, the HS20-44 is multiplied by the overloaded truck factor 1.3 times of. The results show that the ratios of mean maximum values have decreased to 1.93 and 1.55 of moments and shears, respectively. These imply that using the overloaded factor of 1.3 can provide adequate safety level for the bridge design.

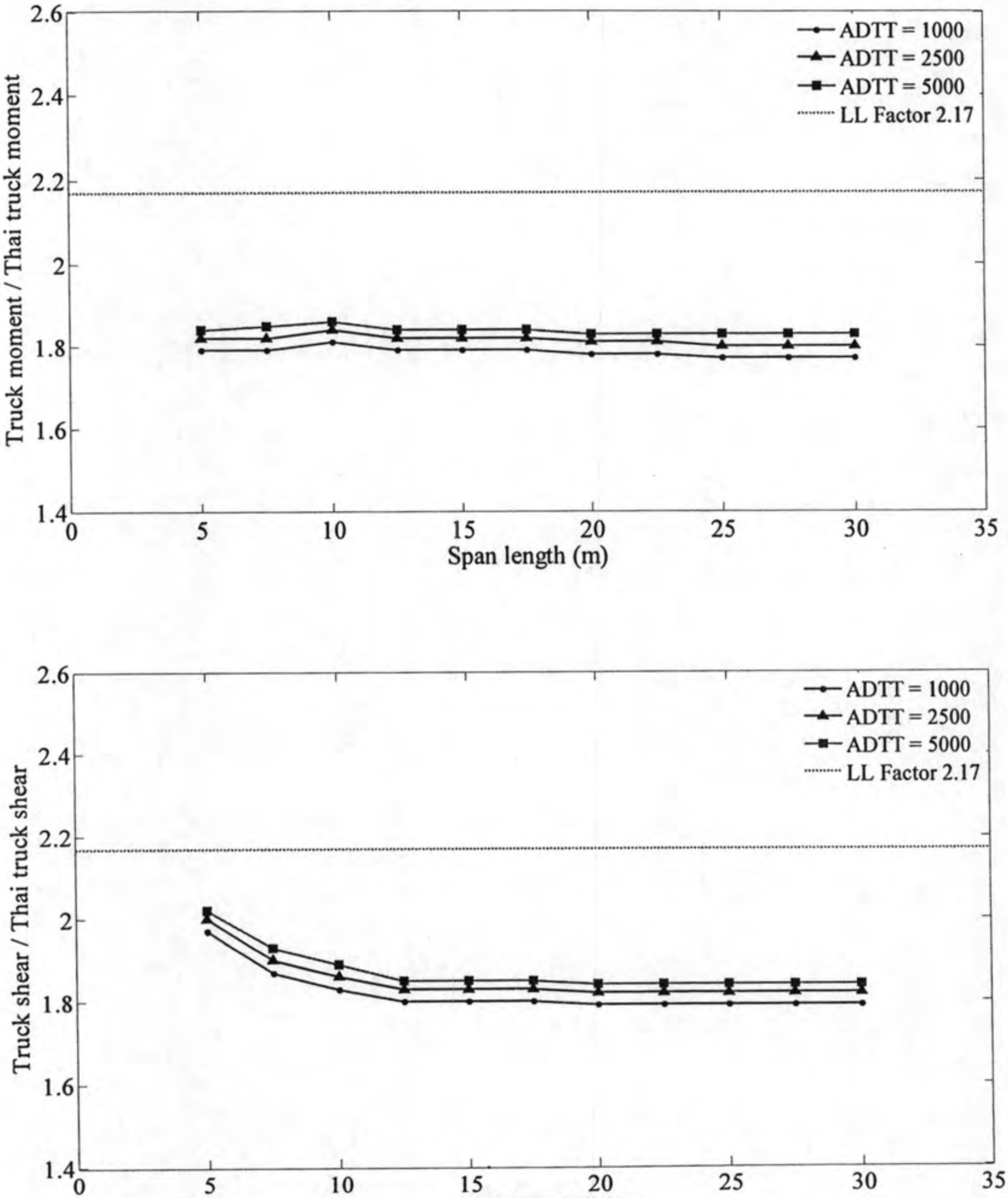


Figure 7.11 Mean maximum (a) moments and (b) shears to design Thai truck load model versus span lengths

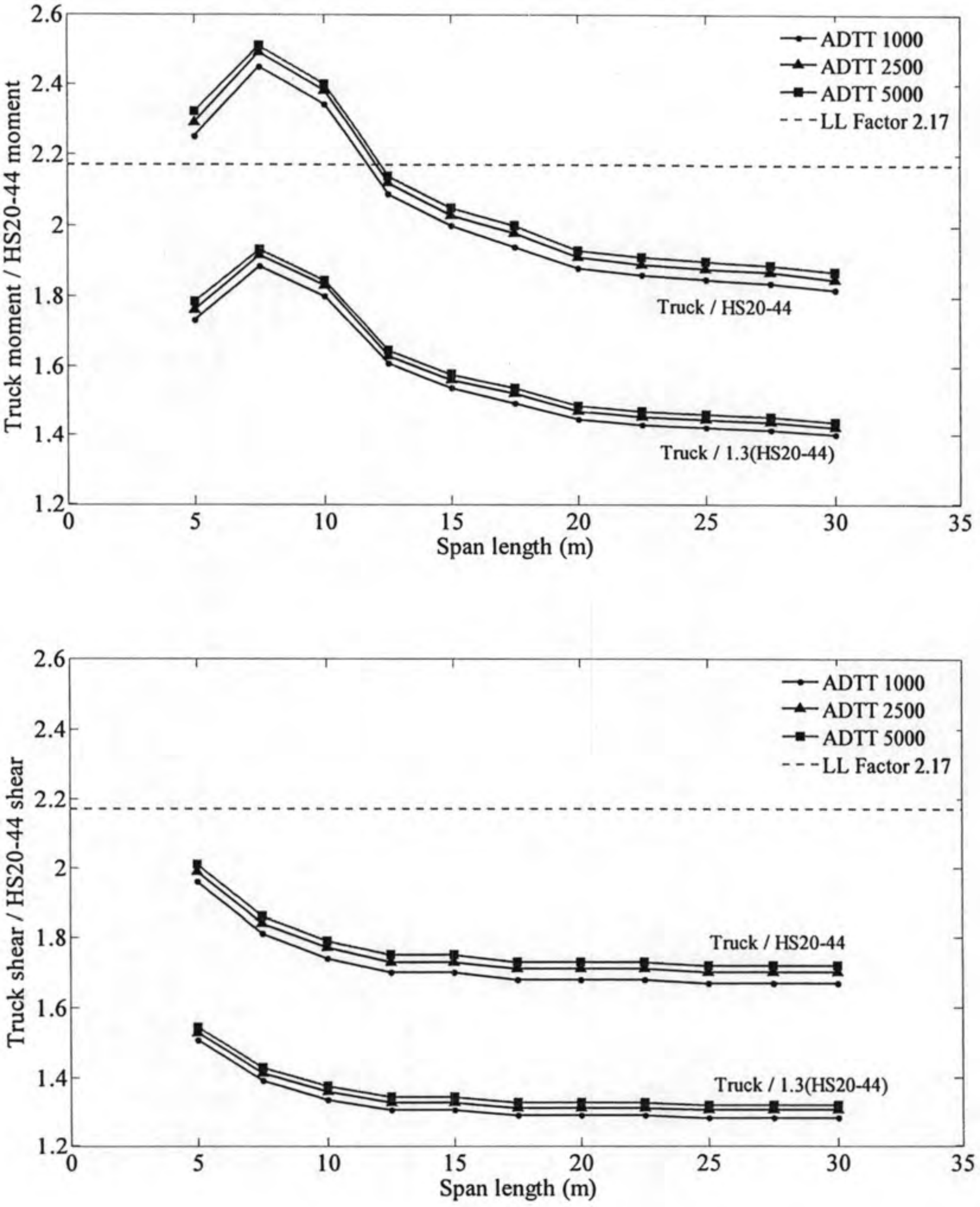


Figure 7.12 Mean maximum (a) moments and (b) shears to the HS20-44 load model versus span lengths

The comparisons of bridge moment and shear induced by the design Thai truck and HS20-44 are shown in Figure 7.13. It is found that the design Thai truck load model governs the bridge design for a short span bridge. Although the design Thai truck load has gross weight less than HS20-44, it can induce the higher internal forces (moments and shears) in the bridge structure than the HS20-44. This is mainly because of the configuration of the design Thai truck load model. Although the 1.3

times the HS20-44 load model governs the bridge design for almost of the span lengths, the design Thai truck model seems to be more appropriate than HS20-44. This is because the design Thai truck load model is more similar to the 10-wheel trucks which are being used in the actual traffic.

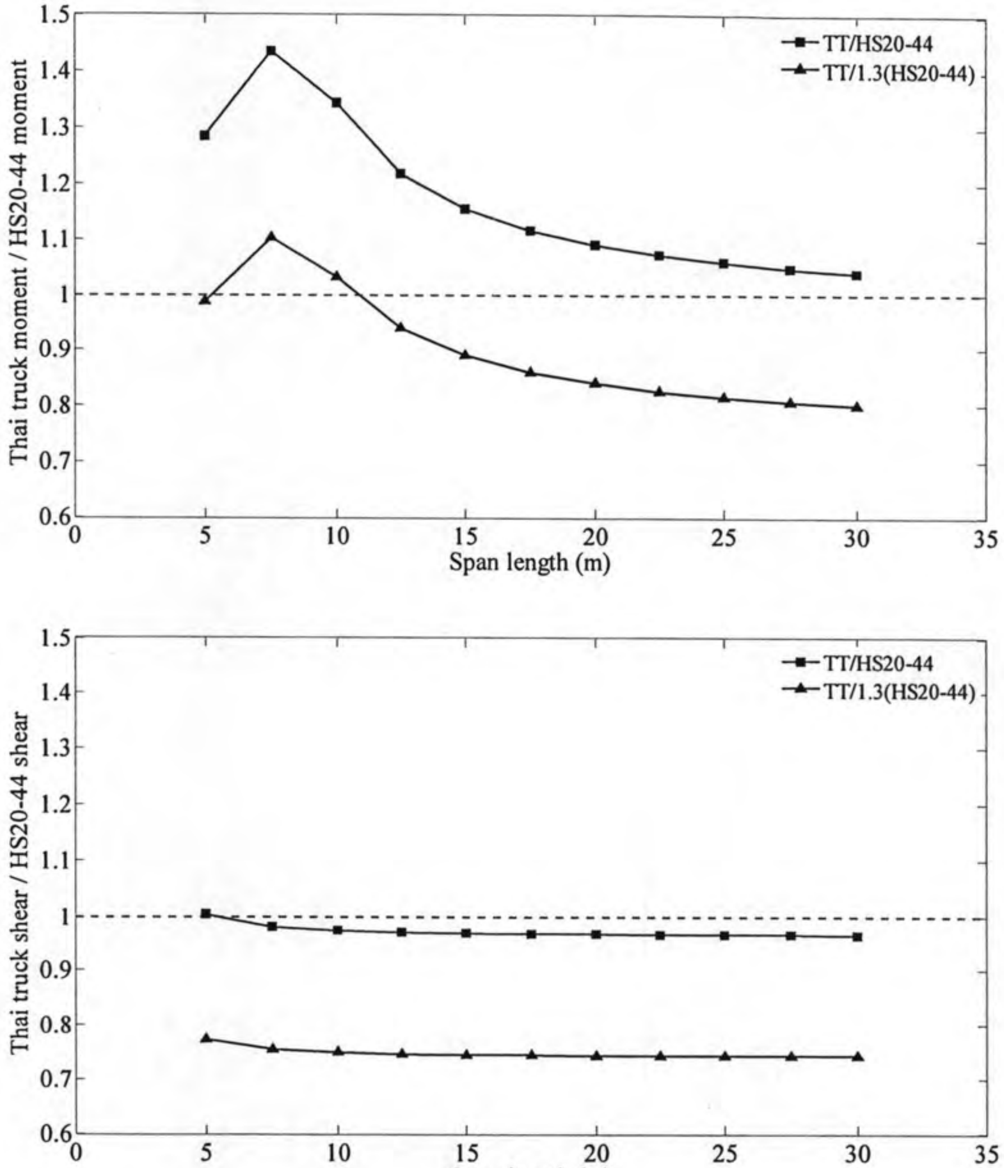


Figure 7.13 Comparison of design Thai truck and HS20-44 for (a) moments and (b) shears versus span lengths

Finally, the suitable live load model for Thai bridge design has been suggested from these obtained results. The existing design Thai truck load model is appropriate to use for the short span bridge design with a live load factor of 2.17. However, using the B-WIM database and extrapolated CDFs graph as shown in Fig 7.14, the current traffic condition could increase the truck load for about 10% which is an adequate safety level for a design life time of 75 years. On the other hand, the results theoretically indicate that the gross weight of the existing design Thai truck load model could be reduced by 10% However, it is noted that previous statement has been proposed based on a limit number of recorded truck data. It is therefore strongly recommend that further long-term truck load monitoring should be conducted in order to establish a more precise design Thai truck load model.

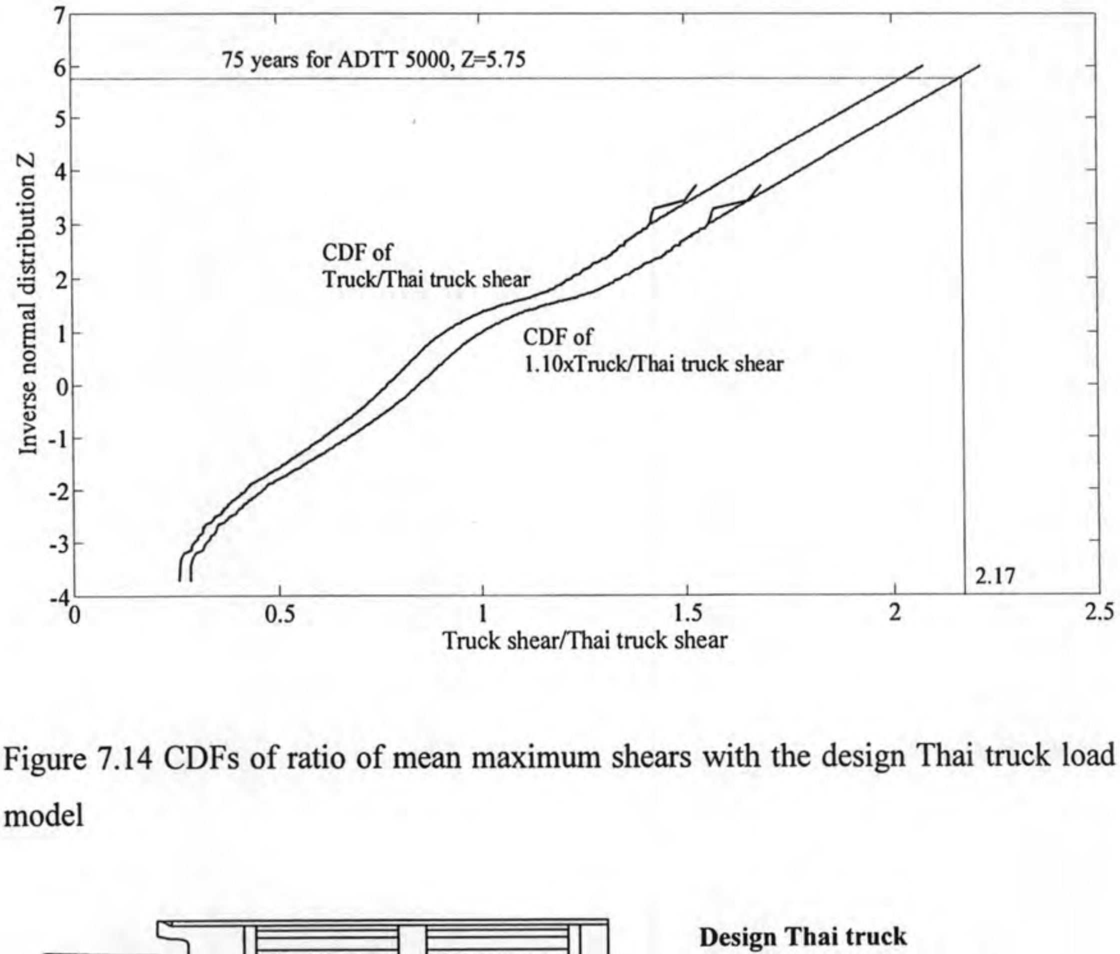
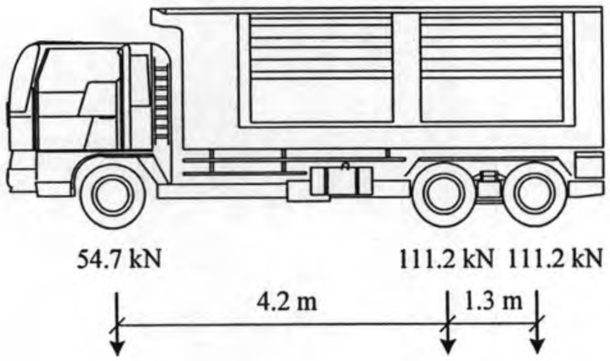


Figure 7.14 CDFs of ratio of mean maximum shears with the design Thai truck load model



Design Thai truck

Front axle wt. = 54.7 kN

Middle and rear axle wt. = 111.2 kN

Gross wt. = 277.1 kN

Axle spacing, S1 = 4.2 m

Axle spacing, S2 = 1.30 m

Fig 7.15 Proposed truck load model

7.5 Summary

The Bridge Weigh-In-Motion system is applied to record 10-wheel truck data in normal traffic condition. The obtained truck databases are composed of the axle weight, truck gross weight, vehicle configuration (axle spacing), vehicle speed and travelling path of truck. The databases cover approximately 5,049 heavy trucks. The results show that the average tandem axle weight and gross weight of 10-wheel trucks are 172.31 kN and 217.28 kN, respectively. The results show that the mean of B-WIM database is not overweight compare with the legal limitations. However, there are 901 trucks (17.85%) that exceed weight limits for the case of tandem axle weight more than 196 kN and 858 trucks (16.99%) that are overweight for the case of gross weight more than 245 kN. These results show that there are a significant number (more than 16%) of overloaded trucks moving in the transportation network.

By comparing the design Thai truck load model with the HS20-44 load model, from which the statistical parameters are derived by using the available truck data, moments and shears then are calculated for various lengths of the short span bridge (5-30 m). The resulting CDFs are extrapolated for longer time periods (up to 75 years for a life time of the bridge design). It is observed that the design Thai truck load model is used to conservatively design the bridge with a live load factor 2.17 for 75 years life time, while HS20-44 is not conservatively used. By comparing the design Thai truck and HS20-44, it is found that the design Thai truck model seems to be more appropriate than HS20-44. This is because the design Thai truck load model is more similar to the 10-wheel trucks which are being used in the present traffic. For the suggested live load model, with the live load factor of 2.17, the gross weight of the design Thai truck load model can be reduced to 10% with the same configurations. It should be noted that if the more surveyed truck database are obtained more accurately, the bridge live load model could then be formulated more conveniently.