Truck Load Distribution and Its Impact on Vehicle Weight Regulations in Taiwan

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Because of the rapid increase in passenger cars on the Sun Yat-sen National Freeway, the percentage of heavy vehicles has decreased gradually from 41 percent in 1980 to 23.91 percent in 1992. However, at the same time the truck overloading problem has become a serious issue and dramatically affects pavement performance life and bridge safety. The first weigh-in-motion equipment was introduced to Taiwan's freeway system. After data collection and analysis, it was found that almost one-sixth of single-unit trucks and one-third of semitractor trailers were heavily overloaded. The overall overloading rate was 14.2 percent above the current regulations, and the tandem axle overloading rate was much higher than the overloading rate of truck gross weights. The data were then compared with the overloading record collected by the freeway patrol for the same period. It was found, surprisingly, that the official record's statistics were much lower than the actual data. It was concluded that overloading, especially axle overloading, is a very serious problem on the freeway system in Taiwan. In addition, the axle load ratios calculated were dramatically different from the ratios given in the bridge design standard specification. Further studies in this direction are highly recommended.

Taiwan's first freeway, Sun Yat-sen National Freeway, was opened to traffic in 1974 for a short section in the northern area; the entire freeway was opened to traffic in 1978. Because of the rapid growth of light vehicles (passenger cars and single-unit trucks), the percentage of heavy-vehicle traffic has decreased gradually from 41 percent in 1980 to 23.91 percent in 1992. However, since 1980 the volume of heavy vehicles has increased at an average annual rate of 7 percent. Taiwan Area National Freeway Bureau (TANFB) collected data at the 10 toll stations along the North-South Freeway. In addition to traffic data, vehicle weights were also collected through the static weigh stations in the toll stations for both directions. Overloaded vehicles are fined on the basis of records. Three out of 10 toll stations can measure the axle weights, and the other 7 can measure only the gross weight of the vehicle. Nevertheless, because of low police enforcement, only a small percentage of heavy vehicles pass through the weigh stations. Most of the overloaded vehicles either pass by the weigh stations or exit ahead of the toll station. Therefore, the actual percentage of overloaded vehicles and their overloading distribution remain unknown. This fact affects not only law enforcement, but also the accuracy of truck load factors, which are very important to highway pavement design and maintenance.

Many research reports and papers on truck weight and law enforcement were reviewed (*1–8*). It was found that heavy vehicle overloading is a serious issue in many countries. Data on vehicle overloading were collected for years in many countries. To solve this problem, many researchers continuously study this area. However, because the actual data on truck weight distribution are not available in Taiwan, no research was done on heavy vehicle overloading. To initiate such research, the first set of weigh-in-motion (WIM) equipment (PAT/bending plate type) was installed on the freeway for this study.

The main objectives of this paper are to

- Analyze the load distribution of all types of heavy vehicles in order to evaluate the reasonableness of the current truck weight regulations and the performance of vehicle load carrying capability,
- Provide comprehensive heavy vehicle load information for pavement and bridge design, and
- Evaluate the performance of law enforcement regarding truck overloading.

Load data from 186,034 heavy vehicles obtained from the introduced WIM system were analyzed and are described herein.

ANALYSIS OF CHARACTERISTICS OF HEAVY VEHICLE WEIGHTS

Truck Percentage Analysis (*K*-Factor)

Using the data base from the WIM system, heavy vehicle population was analyzed. Figure 1 gives a sketch and the legal gross weights of the eight types of heavy vehicles that were analyzed. In Figure 1 U represents the single-unit truck, S represents the semitractor trailer, and F represents the full tractor trailer. Numbers after the letters represent the axle type: 1 for single axle, 2 for tandem axle, and 3 for triple axle.

The *K*-factors for various types of heavy vehicles for both inner and outer traffic lanes were calculated separately. It was found that the U11 truck is most commonly used for freight transportation (K = 16.13 percent) and that the S112 semitractor trailer is the next most commonly used (K = 7.53 percent). The average *K*-factor for both lanes is 28.22 percent, and U11 with S112 account for more than 87 percent of this heavy vehicle population. Although heavy vehicles are not prohibited from using the inner lane except in the climbing section, it was noted that the percentage of trucks in the inner lane was about half that of the outer lane; the ratio is 0.33 to 0.67. In comparing 0.67 with the lane distribution factor of truck traffic, D_L, used for pavement design in Taiwan, it was found that the designated value of 0.9 for a two-lane freeway is considered to be a conservative design.

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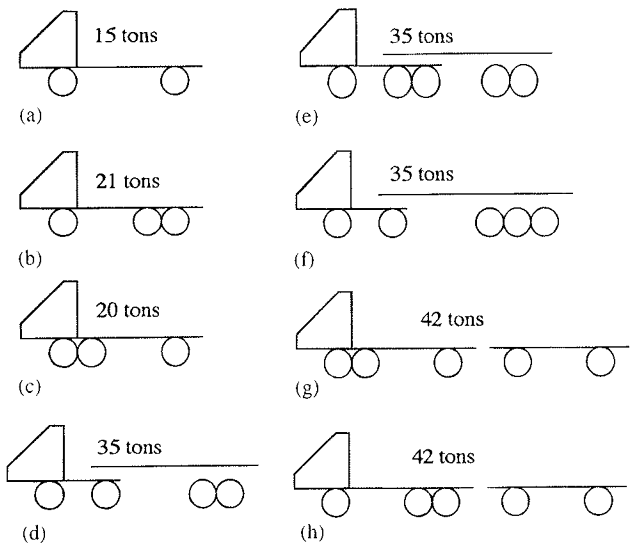

FIGURE 1 Sketches and legal gross weights of various types of heavy vehicles: *a*, U11 truck; *b*, U12 truck; *c*, U21 truck; *d*, S112 semitractor trailer; *e*, S122 semitractor trailer; *f*, S113 semitractor trailer; *g*, F2111 tractor trailer; *h*, F1211 tractor trailer.

Analysis of Gross Weight Distribution for Various Types of Heavy Vehicles

At present, the maximum allowable mass for trucks is governed by the regulations in the Road Traffic Safety Act (*9*). These regulations limit maximum axle loads as well as the maximum gross weight per truck. In this study, the gross weights of various types of heavy vehicles were clustered. Weights in each group were analyzed, and distribution patterns were drawn. Figure 2 illustrates the gross weight distribution for the commonly used semitractor trailer S112. The percentage of overloaded vehicles was calculated for the analyzed vehicles; results are presented in Table 1. It was found that on the basis of legal weight limits, more than 24 percent of the S112 vehicles and 16 percent of the U12 trucks were overloaded. Since the overall overloading rate for both lanes is 14.2 percent above the stipulated regulations, the overloading situation is considered to be a very serious problem in Taiwan.

The average overloading rates for the inner and outer lanes were also calculated. It was noted that the outer lane not only has more heavy vehicles than the inner lane, but its overloading rate is also much higher than the inner lane. This fact indicates that special attention should be given to the calculation of truck load factor (TLF) used for pavement design. The overall average of TLF might not be the adequate value for pavement design, especially for the design of the outer lane. A detailed description is presented in the following section.

Analysis of Overloading Percentage for Discrete Time Intervals in 1 Day

To evaluate the variation of overloading percentages for various vehicle types at different time intervals during 1 day, the vehicle gross weight distributions for the eight types of vehicles were studied separately during weekdays (Monday through Friday) and weekends (Saturday and Sunday). Average heavy-vehicle volumes for various types of vehicles driven on the freeway at 2-hr intervals were calculated, and the overloading percentages for the same period were computed. It was found that overloading percentages increased dramatically from midnight to 6 a.m., with the highest rate, almost 20 percent, occurring from 4 to 6 a.m. (Figure 3). The overloading rate drops thereafter, maintaining an average of 5 to 7

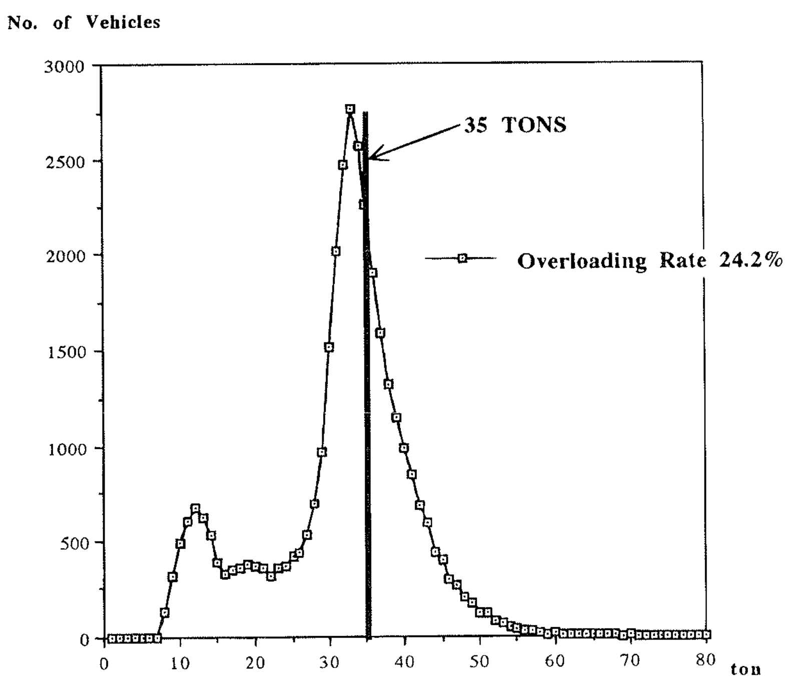

FIGURE 2 S112 gross weight distribution.

TABLE 1 Overloading Rates of Vehicle Gross Weight for Various Types of Heavy Vehicles

	Overloading Rate of Vehicle Gross Weight							
	Single Unit			Semi-Tractor Trailer		Full Tractor Trailer		
Lane	U11	U12	U21	S112	S122	F2111	F1211	All Types
Inner	10.2	20.5	9.7	16.6	16.4	7.5	4.6	11.9
Outer	4.8	12.4	15.5	35.4	52.6	2.7	17.7	15.9
Both	7.8	16.5	13.1	24.2	48.9	3.5	11.4	14.2

percent from 2 p.m. to midnight. The comparison of overloading rates between weekdays and weekend showed the same trend.

Because of the low probability of law enforcement, it is understandable that the highest overloading rate usually occurs in the early morning. Since the WIM station was located in the northern section of the freeway and most cargo and freight are shipped from south to north, this results in the highest overloading rate occurring between 4 and 6 a.m. This is true for weekdays and weekends. The freeway is about 370 km long, so it is suspected that the highest overloading rates for the central and southern sections of the freeway happen between midnight and 4 a.m.

Analysis of Axle Load Weight Distribution

The maximum allowable single-axle load is regulated at 10 T; that of tandem axles is at 14.5 T (*9*). Because triple axles are used only rarely, no regulation is given in Taiwan yet. Since most of the conventional static weigh stations could not measure individual axle loads, vehicles with overloaded axle loads were never fined. Nevertheless, it is believed that actual axle load distributions are a very important source of information for pavement and bridge design, as well as for maintenance.

From the analysis, it was found that the overloading rate in the tandem-axle group (52.6 percent) is much higher than that of the single-axle group (11.9 percent). The S112 semitractor trailer had the highest overloading rate of tandem axles, at 71.1 percent (Table 2). The lowest overloading rate in the tandem-axle group was the U21 truck (1.6 percent). This occurred mainly because the tandem axle of the U21 is a steering axle, which carries a smaller share of the loaded freight. It was interesting to find that the highest overloading rate in the single-axle group was also observed in the U21 truck (31.1 percent). The overloading rates for single and tandem axles of other truck types are presented in Table 2.

Relationship Between Vehicle Axle Load and Gross Weight

From Figures 4 and 5, it was observed that the patterns of axle load distribution for single and tandem axles were different. The diagram of single-axle weight distributions has only one peak, and the overall overloading rate is 11.9 percent. However, not only does the diagram of tandem-axle weight distributions have two high peaks, but the outer lane also has triple the overloading rate of the inner lane. The first peak in the tandem-axle weight distribution is due to empty

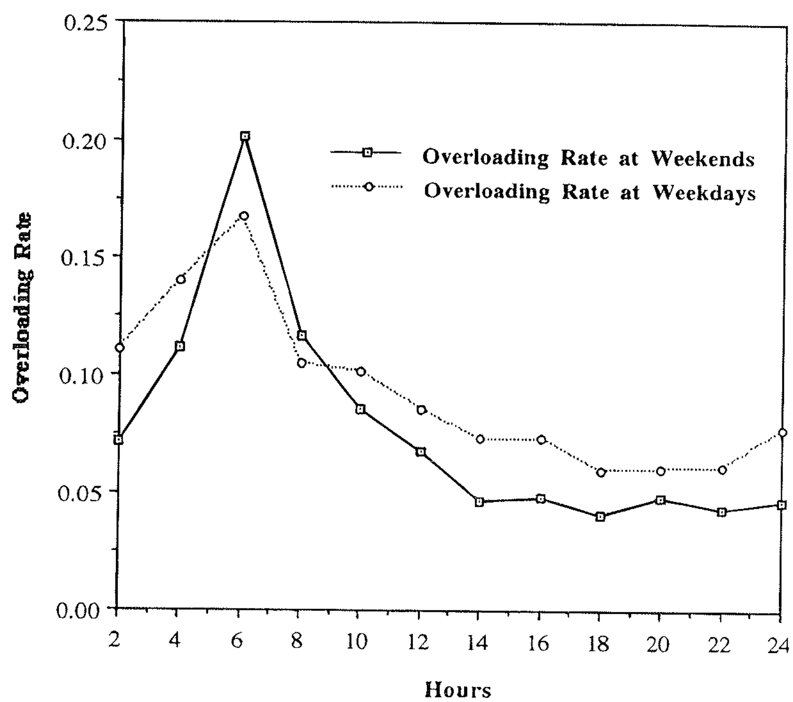

FIGURE 3 Average overloading rates of weekdays and weekends at various time intervals.

TABLE 2 Overloading Rates of Single Axle, Tandem Axle, and Vehicle Gross Weight for Various Types of Heavy Vehicles

	Overloading Rate							
	Single Unit			Semi-Tractor Trailer		Full Tractor Trailer		
Axle Type	U11	U12	U21	S112	S122	F2111	F1211	All Types
Single Axle	6.7	4.7	31.9	24.2	3.4	14.0	6.9	11.9
Tandem Axle	N.A.	18.8	1.6	71.1	26.1	8.9	62.7	52.6
Gross Weight	7.8	16.5	13.1	24.2	48.9	3.5	46.1	14.2

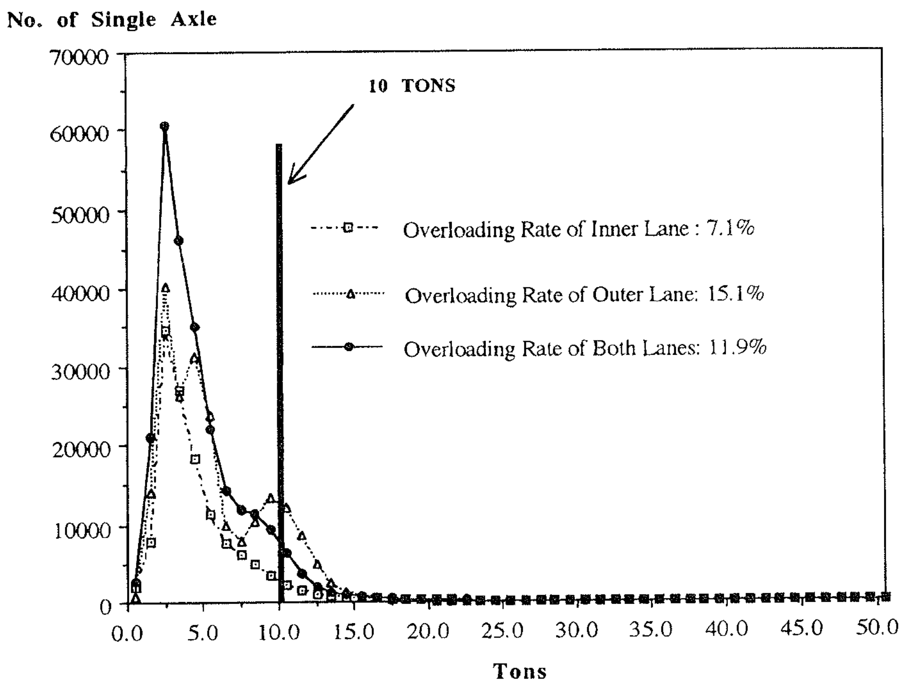

FIGURE 4 Average single-axle load distribution.

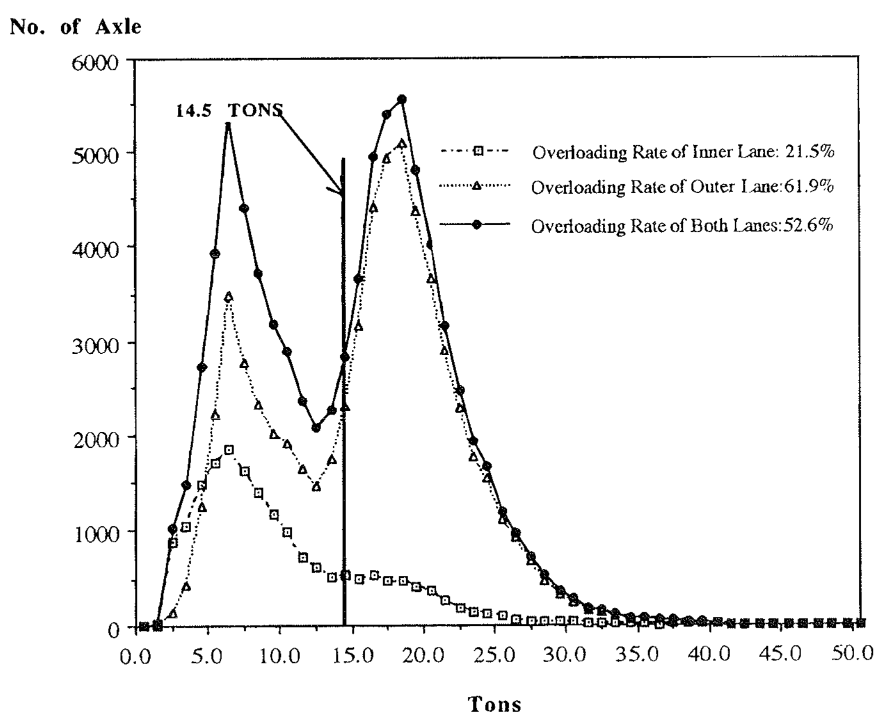

FIGURE 5 Average tandem-axle load distribution.

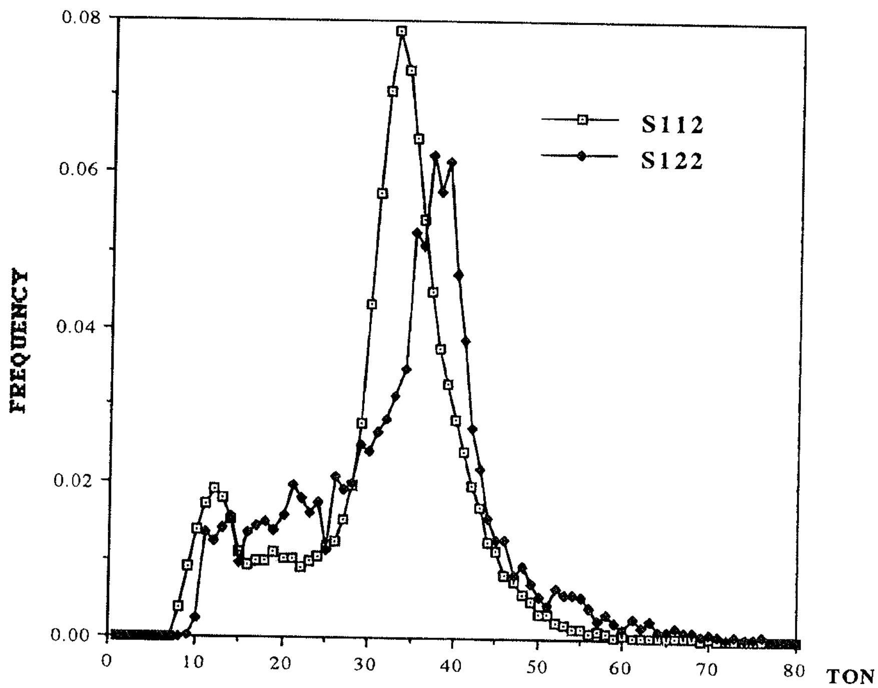

FIGURE 6 Gross weight frequency distribution for S112 and S122.

and lightly loaded trucks, and the second peak is attributed to medium to heavily loaded trucks. Both the horizontal and vertical coordinates for the two peaks will change with the varying degree of a truck's empty rate and overloading rate, respectively. It was noted that the tandem-axle overloading rate is much higher than the overloading rate of the truck's gross weights. In other words, if the truck has a tandem axle, although it does not break the legal gross weight limit, it may still break the legal tandem-axle load limits.

It was observed that S112 and S122 were used mainly to ship very heavy freights, such as coarse aggregates, precast concrete beams, steel beams, and logs. Figure 6 shows the comparison of gross weight distributions of S112 and S122. It was noted that the distribution curves of these two vehicles were very similar. However, because of the different axle configuration, the mean value of gross weight of S122 was about 5 T higher than that of S112. Since both S112 and S122 have the same gross legal weight limits (35 T) in Taiwan, it was found that the overloading rate of gross weight of S122 is about double of that of S112. However, it is interesting that both single- and tandem-axle overloading rates of S122 were much lower than those of S112 (Table 2). These findings indicate that the relationship of current legal weight limits of gross vehicle weight, single-axle weight, and tandem-axle weight is not very rigorous and should be seriously reevaluated. Besides, it was also concluded that the legal gross weight limits for each type of heavy vehicle should be determined by axle configuration instead of general vehicle types.

Recently, the Road Freight Association approached Taiwan's Ministry of Transportation and Communication with a request to increase the legal gross weight limits for trucks. On the basis of findings of this study, a higher gross weight limit would result in even higher overloading rates for single- as well as tandem-axle trucks. It is therefore highly recommended that before any action is taken, the effects of higher legal limits for gross weights, single-axle, and tandem-axle loads on pavement and bridge design, maintenance, and traffic safety be studied.

DETERMINATION OF TLF FOR PAVEMENT DESIGN

AASHTO's *Guide for the Design of Pavement Structures* (*10*) was generally adopted for highway pavement design in Taiwan. In this design, TLF is a very important parameter. In the past, sampling data of truck weights collected by TANFB static weigh stations were used to determine the average TLF for pavement design, although most of the overloaded heavy vehicles were hardly included in the sampling. In this study, it was observed that the calculated TLFs of each type of heavy vehicle were different from inner lane to outer lane. Table 3 presents the TLFs calculated on the basis of WIM data for the typical combination of structure number (SN) 5 and terminal PSI (Pt) 2.5.

The TLF of a single-unit truck in the inner lane is 75 percent higher than that of one in the outer lane. On the contrary, the TLFs of a semitractor trailer and full trailer in the outer lane are higher than those in the inner lane. The average TLF of the outer lane is 26.7 percent higher than that of the inner lane and 11.6 percent higher than the overall average of both lanes. This figure indicates that the underestimated TLF was used for pavement design if the overall average TLF was selected instead of using the average TLF of the outer lane, which usually was designated as the design lane. In other words, the pavement performance life was overestimated in the current design in Taiwan.

Moreover, the U12 truck had the lowest TLF but the highest average gross weight among the single-unit trucks. This indicated that U12 had the best performance in load-carrying efficiency of the single-unit trucks. Likewise, the TLF of S122 was about half that of

TABLE 3 TLF for SN = 5.0, PT = 2.5

	Truck Load Factor										
Lane	U11	U12	U21	S112	S122	F2111	F1211	Single Unit	Semi-Tractor Trailer	Full Tractor Trailer	Overall Average
Inner	2.233	1.891	2.215	4.415	2.130	5.901	2.619	2.183	4.197	3.895	2.347
Outer	1.227	0.986	2.916	5.107	2.985	4.576	5.164	1.247	5.081	5.117	2.974
Both	1.697	1.363	2.684	5.056	2.643	5.064	4.975	1.673	5.006	4.986	2.665

S112, which indicated that the pavement damage caused by S122 was just about half of that caused by S112. However, as mentioned earlier, the average load-carrying capacity of S122 is 5 T above S112. It is concluded that S122 is much more efficient than S112 in load carrying even under the circumstances in which they have the same legal gross weight limits.

COMPARISON OF PERCENTAGE OF ACTUAL OVERLOADING WITH LAW ENFORCEMENT RECORDS

The highway patrol reports vehicles that are overloaded by more than 10 percent to the control center. Based on the statistical data of the 1992 annual report published by TANFB, the total number of reported overloaded vehicles was 61,236 (*11*). However, for the entire freeway the total number of heavy vehicles recorded in the same report was 72,291,109. The rate of overloaded vehicles as reported is 0.085 percent. However, the WIM system recorded 186,034 trucks, 16,179 of which were overloaded by more than 10 percent of their legal gross weight limit. Using the WIM data, the overloading rate was calculated as 8.7 percent. By comparing these two rates, it was found that fewer than 1 percent of overloaded vehicles were reported by the highway patrol.

This figure indicates that only a very small percentage of overloaded vehicles were found on the existing freeway system. Since the freeway has more police resources than other highway networks, it is possible that an even lower percentage of overloaded vehicles are reported from those other highways.

HEAVY-VEHICLE AXLE LOAD RATIO AND ITS IMPACT ON BRIDGE AND PAVEMENT DESIGN

The axle load ratios of some specific heavy vehicles are important factors in bridge and pavement design, particularly when only the gross weights but not the actual axle loads are known. Traditionally, fixed axle load ratios were selected for two types of heavy vehicles for bridge design, as shown in Figure 7 (*12*). In this paper, axle load ratios for all types of heavy vehicles at various levels of gross weight are computed. Figures 8 and 9 present the axle load ratios at various gross weight levels for vehicle types U11 and S112. It was found that all axles increased their loads with increased gross vehicle weights, but none had a fixed axle load ratio. The axle load ratio of U11 is between 1.05 and 1.48, with an average of 1.15. This number is significantly different from the H standard truck used in the bridge design specification, as shown in Figure 7. Likewise, the axle load ratios of S112 are also different from those of the standard HS truck shown in Figure 7. These findings could provide bridge engineers with more valuable information and may be further studied in order to update the bridge design specification.

CONCLUSIONS

For this paper truck weights were collected by installing the WIM on the national freeway. From the analysis, it can be concluded that the overloading situation is much more severe than the official record shows. It can also be concluded that the WIM system can overcome the shortcomings of conventional static weigh stations. The following conclusions were drawn:

1. The average overloading rate for heavy vehicles is higher on weekdays than on weekends. The highest overloading rates on weekdays and weekends occur from 4 to 6 a.m., the highest percentage being 20.2.
2. The overloading rate of the outer lane is higher than on the inner lane, except for single-unit trucks. The actual overloading rates for these two lanes can be used as a reference for future pavement design. The overall overloading rate of vehicle gross weights is 14.2 percent.
3. The overloading rate of the tandem-axle group (52.6 percent) is much higher than that of the single-axle group (11.9 percent), and the S112 truck has the highest overloading rate among the tandem-axle group (71.1 percent).

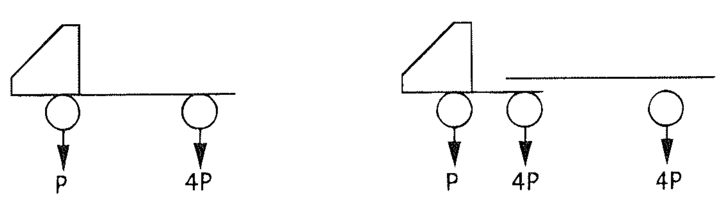

FIGURE 7 Axle load ratio of standard trucks used for highway bridge design: *left*, H truck; *right*, HS truck.

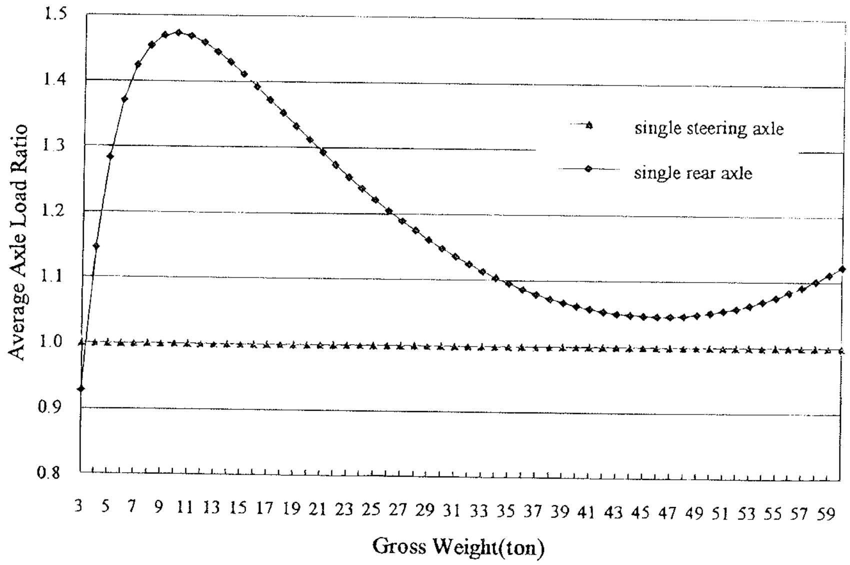

FIGURE 8 Individual axle load ratios of U11 truck for various gross weights (use single steering axle as base).

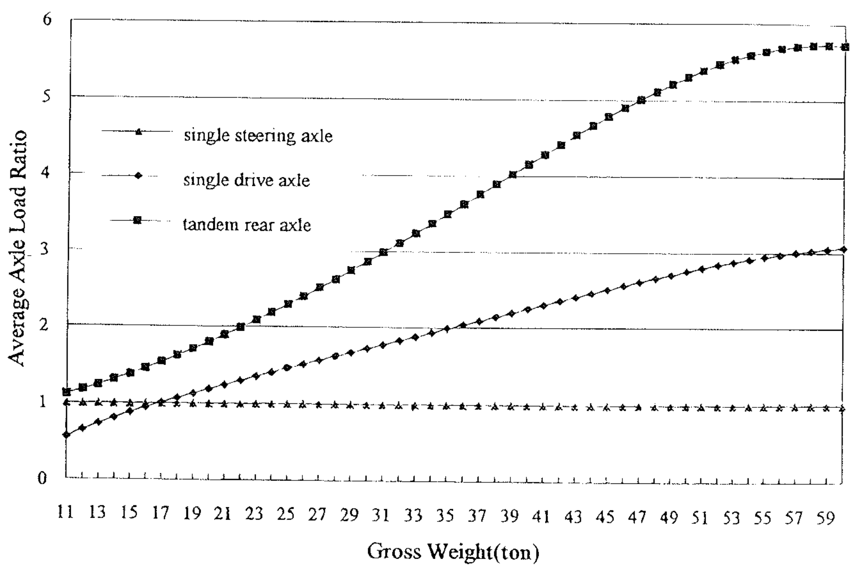

FIGURE 9 Individual axle load ratios of S112 semitractor trailer for various gross weights (use single steering axle as base).

4. The traffic lane distribution factor, D_L, used in the pavement design specification was overestimated and the selected TLF was underestimated in the design. Both factors should be studied further to update the design specification.

5. The U21 truck has the highest overloading rate among the single-axle group (31.9 percent), the lowest overloading rate among the tandem-axle group (1.6 percent), and the largest TLF among the single-unit trucks. This indicated that U21 is not an efficient load-carrying vehicle, and its future use should be discouraged.

6. Not only the overloading rates of the single-axle and tandem-axle trucks but also the TLF of the S122 are much lower than those of S112 at the same legal gross weight limit. The S122 was much more efficient in load carrying than S112, and the gross weight limits of these two trucks should be different.

7. The actual overloading rate of vehicle gross weights is 100 times higher than the official records.

8. The axle load ratios for standard H and HS trucks obtained from this paper are dramatically different from those of the AASHTO standard specifications. The ratios should be evaluated carefully in order to update the design specification.

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