Effects Of Overloaded Heavy Vehicles On Pavement And Bridge Design In Taiwan

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ABSTRACT

As a developing country, a large number of infrastructure projects have been undertaken in Taiwan in recent years. Due to these large scale constructions, not only has the number of heavy vehicles (especially the aggregate-hauling trailers and dump trucks) grown rapidly, but the size and weight of heavy vehicles has also increased dramatically. These factors induced a very serious truck overloading problem which significantly affects pavement performance and bridge safety.

In this study, the weigh-in-motion (WIM) equipment was introduced in Taiwan's freeway systems. After data collection and analysis, it was found that the computed average truck load factor (TLF) for combined heavy vehicles from the WIM data collection was 2.7 times higher than the original design value which already considered 30 percent truck overloading. It was also found that computed axle load ratios for various types of heavy vehicles were dramatically different from the ratios given in the bridge design standard specification. Bridge deck designs for a simply supported bridge were studied based on the average designed truck weight and its axle load ratio derived from the WIM data analysis as well as the existing specification. It was concluded that the current bridge design standard specification will result in a 28 percent underestimation of steel volume in bridge deck design.

PREVIOUS STUDY OF OVERLOADED HEAVY VEHICLE WEIGHTS

The first freeway (National Freeway 1) was fully opened to traffic in 1978. Due to the rapid growth of light vehicles (passenger cars), the percentage of heavy vehicle traffic has gradually decreased from 41% in 1980 to 23.91% in 1992. However, since 1980 the volume of heavy vehicles has increased at an average annual rate of 7%. Data collection was done by the Taiwan Area National Freeway Bureau (TANFB) through the ten toll stations along the North-South Freeway. In addition to the traffic data, vehicle weights were also collected through the static weigh stations beside the toll stations in both directions. Four out of ten toll stations can measure the axle weights and the other six can only measure the gross weight of the vehicle. Due to 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 make an exit ahead of the toll station. Therefore, the actual percentage of overloaded vehicles and their overloading distribution remains unknown. This fact does not only affect law enforcement, but also affects the accuracy of truck load factors (TLFs) which are very important to highway pavement design and maintenance.
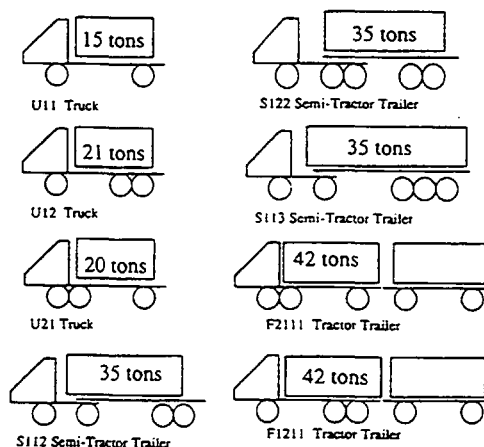

Figure 1 Sketch and legal gross weights of various types of heavy vehicles.

The first set of WIM (PAT/ bending plate type) equipment was installed on National Freeway 1 in May 1992 by the National Taiwan University (NTU) research group. The average truck percentage of the traffic (K factor) was 28.22%, and load data for a total number of 186,034 heavy vehicles (15 tons and above) were collected. Based on the data base from the WIM system, the weight distribution and overloading situations for various types of heavy vehicles were analyzed [1]. Figure 1 gives the sketch and the legal gross weights for the analyzed eight types of

heavy vehicles. In Figure 1, U represents single unit trucks, S represents semi-tractor trailers, and F represents full tractor trailers. Numbers following the alphabetical letter U, S, and F represents the axle type, i.e., 1 for single axle, 2 for tandem axle , and 3 for triple axle. Figure 2a shows the vehicles percentage distribution by various truck types. It was found that the U11 truck is most commonly used for freight transportation (62%), and the S112 semi-tractor trailer is the next most commonly used (20%). Together, both types account for more than 82% of the heavy vehicle
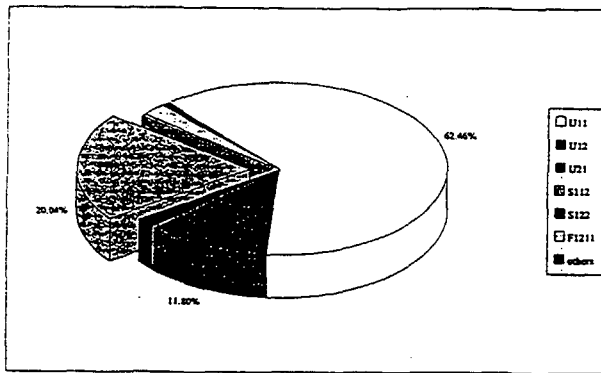

Figure 2a Truck volume distribution of National Freeway 1.

population. However, not only the traffic volume but also the weights affect the pavement performance significantly. Since the AASHO Road Test, the relationship between traffic axle load and pavement damage has been in terms of the fourth power law, i.e. an axle load twice as large as another will cause sixteen times the equivalent damage. Based on the AASHTO Pavement Design Guide [2], the equivalent single axle load (ESAL) concept has been developed to convert the axle loads of mixed traffic into a single unit for the pavement structural design. The damage caused by one ESAL is defined as the damage caused by an 18-kips single axle load. Figure 2b displays the distribution of truck types in terms of ESALs. It was observed that U11 counts for 40% of the total ESAL, and 43% of the damage is caused by S112. With respect to trucks, damage from the S112 truck is more substantial, because this type of truck causes 43% of damage to the pavement structure with only 20% of the truck volume.
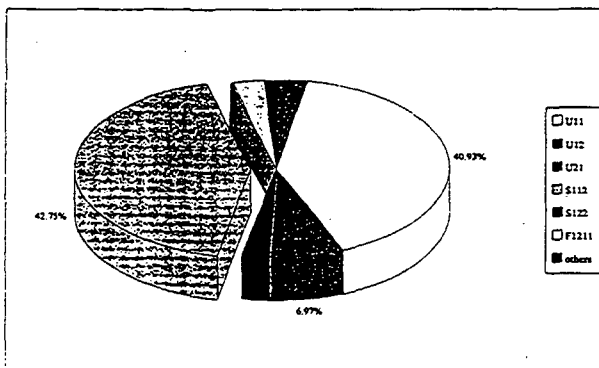

Figure 2b ESALs distribution by truck types of National Freeway 1.

This is mainly due to the substantial axle load overloading.

At present, the maximum allowable mass for trucks is governed by the regulations in the Road Traffic Safety Act [3]. These regulations limit maximum truck axle loads as well as the maximum gross weight. However, the maximum gross weight for a given truck was defined by the truck type (i.e. 2-axle single unit tuck, 3-axle single unit truck, semi-tractor trailer, and full tractor trailer) rather than the truck axle numbers and axle configuration. For example, semi-tractor trailers with 4, 5, or 6 axles have the same maximum gross weight (35 tons) and no other regulations such as Bridge Formula were required to be followed. Based on the WIM study of National Freeway 1, the overall overloading rate of gross vehicle weight was found to be 14.2% above the stipulated vehicle weight regulations and S112 had the highest overloading rate of 24%. From the analysis of axle loads distribution, it was also found that the overloading rate in the tandem axle group (52.6%) is much higher than that of the single axle group (11.9%). Again, the S112 semi-tractor trailer had the highest overloading rate of tandem axles, at 71.1%. It was observed that in Taiwan S112 and S122 were used most commonly to ship very heavy freight, such as coarse aggregate, precast concrete beams, steel beams, and logs. From the data analysis, both type of vehicles have very similar gross weight distribution, but the mean values of the gross weight for S122 was about 5 tons higher than that of S112 (Figure 3). Based on Taiwan's vehicle weight
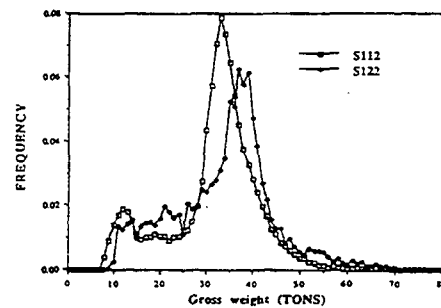

Figure 3 Gross weight frequency distribution for S112 and S122 of National Freeway 1.

regulations, both S112 and S122 have the same gross legal weight limits (35 tons). However, S112 occupies more than 90% of the semi-tractor trailer market , because its purchasing price is US $24,000 less than S122 in Taiwan. Figure 4 clearly shows that the overloading rate of the gross weight for S122 is about double that of S112, but both single and tandem axle overloading rates for S122 are much lower than those of S112. It is known that pavement design is based on the expected accumulative equivalent single axle loads (S ESAL), these findings indicate that S112 causes much higher damage on pavement than S122 for the same vehicle gross weight. It also indicates that the regulations for current legal weight limits of gross vehicle weight, single axle weight, and tandem axle weight are not compatible, and they should be seriously re-evaluated.

Figure 4 Overloading rates for U11, U12, S112, and S122 of National Freeway 1.

WEIGHT DATA ANALYSIS FOR NATIONAL FREEWAY 3

From the literature review it was understood that the problem of heavy vehicle overloading is a very serious issue in many countries and many researchers continuously study in this direction in order to solve this problem [4,5,6,7,8,9]. However, the previous study was the only research effort emphasizing the problem of heavy vehicle overloading in Taiwan. In order to continue the research study on this topic, the NTU research group recently installed another set of weigh-in-motion (WIM) equipment on a second Freeway (National Freeway 3). The main objectives of this study are to

(1) evaluate the vehicle weight distribution of heavy vehicles and compare the results with the previous study,

(2) study the truck load factors (TLFs) and axle load ratios of various heavy types for pavement and bridge design .

The proposed total length of National Freeway 3 is around 400 km. The northern section was first completed and open to traffic on August 24, 1993. This section connects the Taipei and Shinchu cities and in general parallels National Freeway 1 (Figure 5). The other portion of National Freeway 3 is still either under design or construction. Since this opened section length is only 65
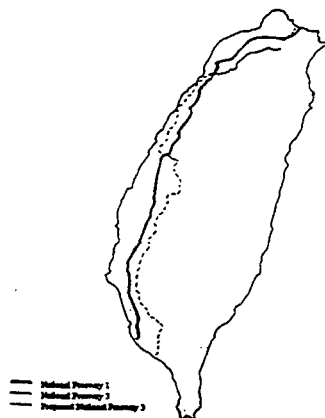

Figure 5 Plot of National Freeway 1 and proposed National Freeway 3.

km and the local connecting highways at the Taipei end are not well designed, only a small percentage of traffic was attracted to National Freeway 3 from National Freeway 1 even though it has been open to traffic for more than one and a half years. However, it was surprisingly found that a relative large portion of this section in the north bound direction was severely deteriorated and therefore was overlaid. In this study, a set of WIM (TRUVELO/ capacitance weightpads type) equipment was installed on National Freeway 3 in April 1995. The WIM equipment in the test section consists of one weightpad and two inductance loop detectors in each lane. The arrangement of the devices is shown in Figure 6. The loop detector
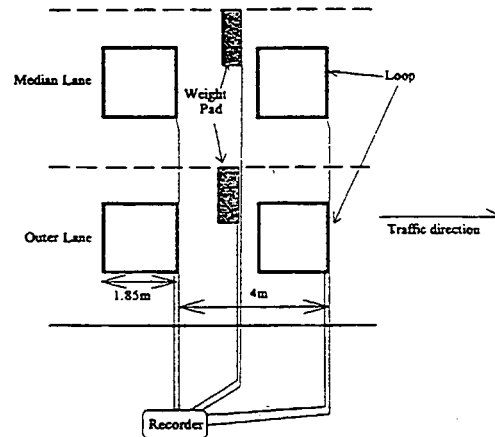

Figure 6 Arrangement of WIM system

recognizes the presence of a vehicle; then the weighpads weigh each wheel and count the number of axles per vehicle. The two loop detectors in each lane are 4 meters apart. This distance divided by the time required for each axle to travel between the two loop detectors represents the vehicle's traveling speed. The axle spacing is calculated by measuring the time interval between successive wheels crossing the weightpad and multiplying this time by the calculated speed. Trucks with different axle number and spacing were then classified into different vehicle types. From the WIM equipment, various types of information can be obtained. Among them, the truck percentage and ESALs by vehicle types, overloading rates of single axle, tandem axle, and vehicle gross weights, and truck axle load ratios will be discussed in this paper.

A total number of 13,676 heavy vehicle data were collected and analyzed. Figure 7a shows vehicle percentage distribution by various truck classification for National Freeway 3. Same as the findings from National Freeway 1 analysis, vehicle types of U11 and S112 account for the majority of the heavy vehicle population (more than 90%), but S112s make up 47% of the total truck volume while U11s account for 44%, which is lower than that of National Freeway 1. However, it has totally different distribution of vehicle types in terms of ESALs (Figure 7b). Only 6% of damage is caused by the U11, and 91% is caused by S112. Again it strongly indicates that the S112s cause the most damage to the pavement structure, and the axle load and vehicle gross weights should be examined carefully. However, since the U11 and S112 types of vehicles are used more commonly than the others, the

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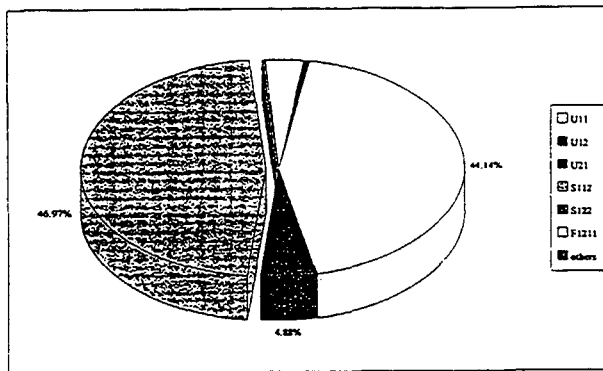following weight analysis is concentrated on these two types of vehicles.

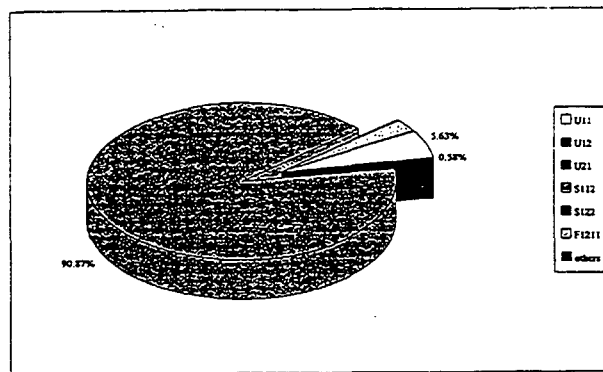Figure 7a   Truck volume distribution of National Freeway 3.

Figure 7b ESALs distribution by truck types of National Freeway 3.

WEIGHT ANALYSIS OF U11

The axle load distribution of U11 was first analyzed. It was clearly observed from Figure 8 that none of the first axles of U11 were overloaded. This was because the steering axle can hardly ever be overloaded. However, 12.8% of the rear single axles were overloaded and the average weight of this axle was only 6.34 tons. Figure 9 shows the overloading rates for axle loads and gross vehicle weights for U11 and S112. It was noted that the overloading rates for single axle loads (6.4%) and vehicle gross weights (9.2%) of U11 are very compatible with the analyzed results from the previous vehicle weight study as shown in Figure 4. Figure 10 gives a closer view by drawing the two gross weight distributions of U11 together. It is obvious that weight data collected from both Freeways have very similar distribution patterns, but the weight distribution curve of National Freeway 3 is higher than that of National Freeway 1. The average U11 vehicle gross weights for both Freeways were also calculated and it was found that the values were 9.0 tons and 9.5 tons for National Freeways 1 and 3, respectively. It was concluded that the vehicle gross weight of U11 is very consistent even at different times and locations.
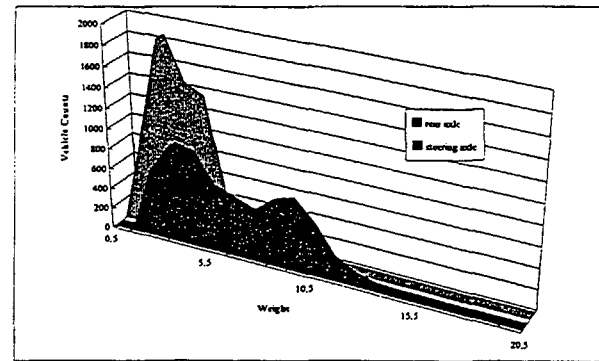

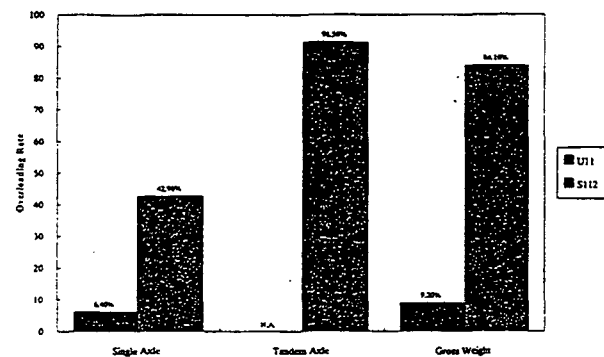Figure 8 Axle weight distribution for U11 of National Freeway 3.

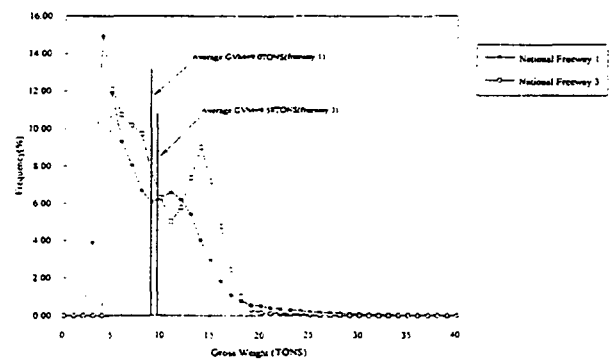Figure 9 Overloading rates for U11 and S112 of National Freeway 3.

Figure 10 Gross weight distribution for U11 of National Freeways 1 and 3.

WEIGHT ANALYSIS OF S112

gure 11 illustrates the axle load distribution of S112. Same as U11, the steering axle of S112 is seldom overloaded, but more than 85% of the second single axles were overloaded and its average weight was 23% above the legal limits (10 tons). Moreover, the tandem axle had a 91% overloading rate and the average axle load was 58% above the stipulated legal limit (14.5 tons). These findings expose the severity of the S112 axle overloading problem. From Figure 9, it was also observed that the overloading rates of vehicle gross weight, single axle load, and tandem axle load for S112 were much higher than those of
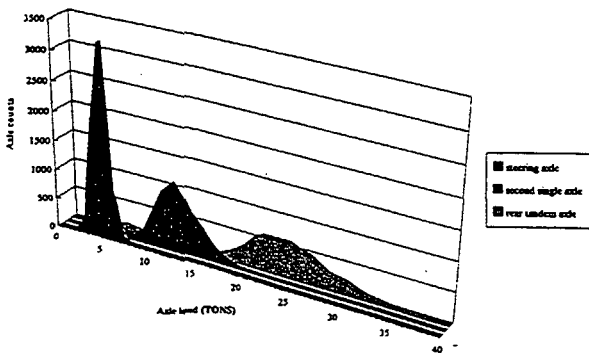
Figure 11 Axle load distribution for S112 of National Freeway 3.

National Freeway 1. More than 84% of the S112 were overloaded and the average vehicle gross weight was 40.4
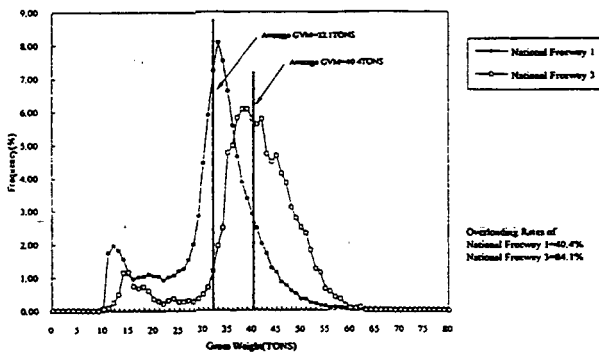

Figure 12 Gross weight distribution for S112 of National Freeways 1 and 3.

tons which is 5.4 tons above the stipulated weight limit (35 tons). Figure 12 displays the gross weight distribution curves for S112 based on the data collected and analyzed from both Freeways. Although these two curves have a similar distributed pattern, National Freeway 3's curve is shifted to the right about five tons higher than that of National Freeway 1, and the average vehicle gross weight of the former is 8.3 tons higher than that of the latter. It is apparent that the S112 samples collected from National Freeways 1 and 3 were not drawn from the same populations. The research panel took a field trip to the WIM site on National Freeway 3 and observed that more than 90% of S112 were coarse aggregate-hauling semi-tractor trailers. However, the data of S112 collected from National Freeway 1 were for semi-tractor trailers with all types of freight shipping purposes. The mean value of vehicle gross weight of S112 for aggragate shipping is significantly higher than that of S112s for other shipping purposes.

EFFECTS OF OVERLOADED VEHICLES ON PAVEMENT PERFORMANCE

From the above analyzed results, it is understood that both National Freeways 1 and 3 have very serious vehicle overloading problems. The truck load factor (TLF, the
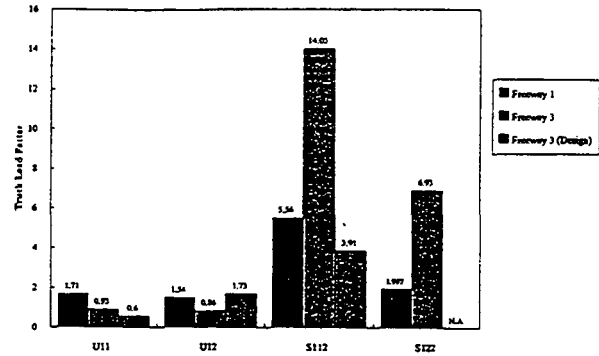

Figure 13 Truck load factors for U11, U12, S112, and S122 of National Freeways 1 and 3, and design value of National Freeway 3.

average ESALs per truck) for U11, U12, S112, and S122 for both Freeways were calculated and presented in Figure 13. In this Figure the truck load factors originally used for National Freeway 3 design were also presented. Most of the designed trucks' TLFs were substantialy underestimated while comparing the values obtained from National Freeway 3 WIM equipment, except truck type U12. It was found that U12 rather than S112 was accountable for coarse aggregate hauling vehicles in the original design, and was considered as overloaded 70% above the stipulated weight limit. Besides, 10 percent of U12 trucks for other shipping purposes were specified overweight 30% over the stipulated weight limit. These assumptions resulted in the relatively large TLF of U12. Nevertheless, due to the low estimation of TLFs for the other truck types the combined TLF for all types of truck used in the pavement design was 2.71, while the overall average TLF calculated based on the WIM data base was 7.26, almost 2.7 times as large as the assumed value. This underestimated TLF resulted in a significant difference between the predicted and actual (from WIM data base) accumulated ESALs.

As shown in Figure 14, the difference between the predicted and actual ESALs during the first a year and seven months was 5,572,000 ESALs, the actual ESALs was 2.3 times as large as the predicted ESALs. The calculations for both predicted and actual ESALs were based upon the actual traffic volumes collected through the toll station which is near the WIM site. Therefore, the
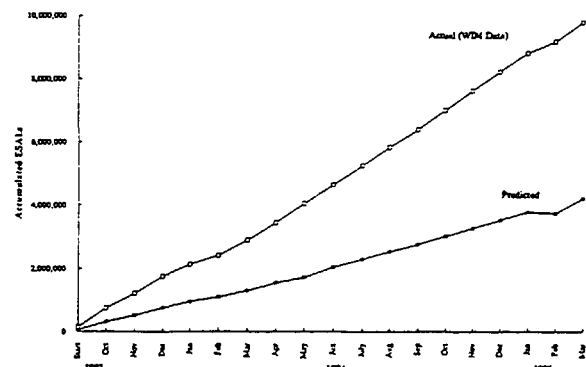

Figure 14 Comparison of the predicted and actual ESALs.

difference between these two ESALs was solely due to the extraordinary truck overloading not other factors. The large difference in ESALs indicates that the damage caused by the overloaded heavy vehicles to the pavement structure is far above the design engineers's expectation. This fact completely coincides with the pavement distress condition observed on National Freeway 3. Although the structural number (SN=6) of the flexible pavement is relatively high and the test section only has been open to traffic for a year and seven months, the outer lane which serves most of the heavy vehicles has experienced severe rutting and alligator crackings especially at the incline section. Due to the low riding comfort, a relative long portion of this section has been milled and overlaid.

EFFECTS OF OVERLOADED VEHICLES AND AXLE LOAD RATIOS ON BRIDGE DESIGN

The axle load ratios of some specific heavy vehicles are important factors in bridge design, particularly under the circumstance that 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 in bridge design as shown in Figure 15 [10] Vehicle gross weight

various gross weight levels for the most commonly used trucks, U11 and S112. It was found that all axles increased their loads with increased gross vehicle weights, but neither U11 nor S112 has a fixed axle load ratio. This can be viewed more clearly in Figures 17a and 17b. The axle load ratio of U11 is between 1.5 to 2.5 with an average of 2.2. This number is significantly different from that of the H
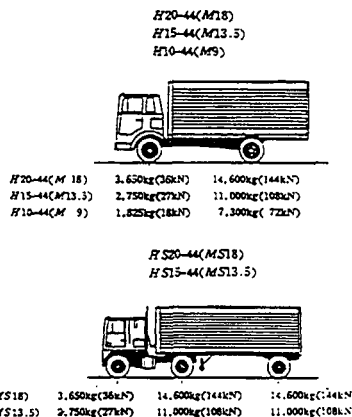
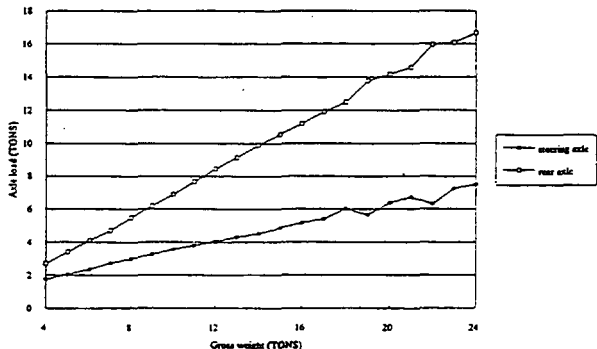Figure 15 H and HS trucks used in Standard Specification for Highway Bridges [10].

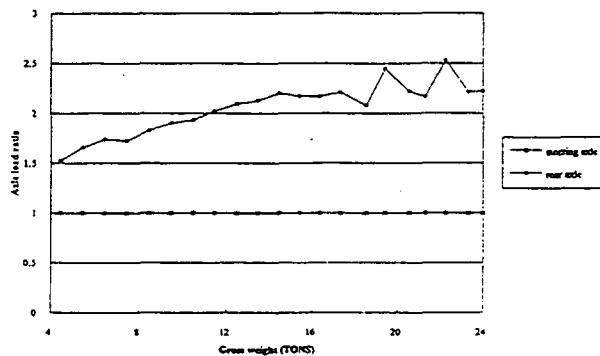Figure 16a Axle load distribution for U11 of National Freeway 3.

Figure 17a Axle load ratio distribution for U11 of National Freeway 3 (use the streering axle as base).
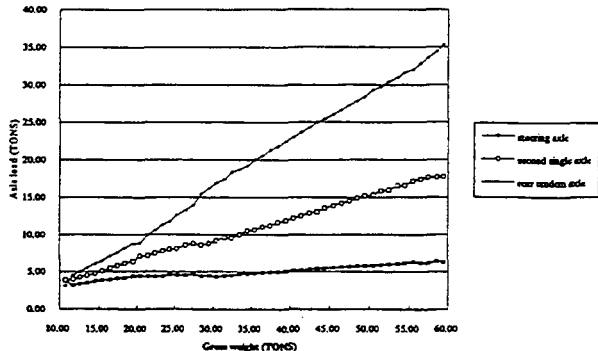
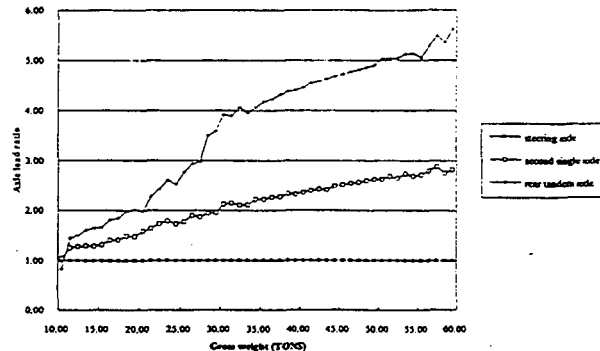Figure 16b Axle load distribution for S112 of National Freeway 3.

was subdivided into each axle based on the given axle load ratios. In this study, axle load ratios for all types of heavy vehicles at various levels of gross weight were computed. Figures 16a and 16b present the individual axle loads at

Figure 17b Axle load ratio distribution for S112 of National Freeway 3 (use the streering axle as base).

standard truck that is shown in Figure 15. Likewise, the axle load ratio of the S112 varies with different vehicle gross weights, and it is dramatically different from the axle load ratio of the standard HS truck used in Bridge Design Specification as shown in Figure 15. Truck type HS20-

44(MS18) was selected for bridge design for National Freeways 1 and 3. In order to take the vehicle overloading into account, the designed vehicle gross weight (32.85 tons) plus 30% overloading weight (i.e. 9.86 tons) was used for the bridge deck design in Taiwan, and the specified axle load ratio of 1:4:4 was used to divide the gross weight into axle load weights. However, in this study it was found that it is S112 rather than the standard HS20 that should be seriously taken into account for bridge design; and an adequate axle load ratio should be selected to reflect the real axle load distribution condition of S112.

CASE STUDY OF BRIDGE DECK DESIGNS WITH HS20 AND S112

A simply supported bridge deck design was studied by applying the HS20 truck, HS20 truck with 30% overloading, and S112 truck respectively. The bridge deck

was 22.8 m wide with nine precast prestressed I-girders as shown in Figure 18. When applying the HS20 truck for design, two loading cases, i.e. standard vehicle gross weight (32.85 tons) and 32.85 tons with 30% overloading (42.7 tons), and the fixed axle load ratio of 1:4:4 were selected which resulted in the designed wheel loads of 7.3 tons and 9.49 tons for two different conditions respectively. The additional 30% overloading factor has been adopted in the Freeway bridge deck design as a conservative consideration for years. In another case, the mean vehicle gross weight of S112 and its corresponding axle load ratio of 1:2.4:4.6 was selected as the live load parameters for bridge deck design. The designed wheel load was then calculated as 11.62 tons. Based on the Bridge Design Specification, the bending moment due to the vehicle live load for a meter long slab is calculated as following:
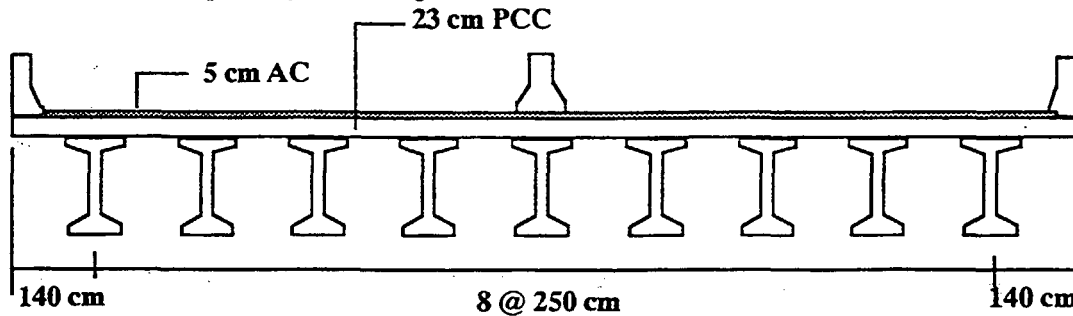

Figure 18 Diagram of bridge cross secioon used in the case study.

$$M_{L.L.} = [(S + 0.6) / (9.6)] * P \qquad (1)$$

where

$M_{L.L.}$: bending moment due to vehicle live load, kg-cm

$$S = (2.5-T) + (T / 2), cm \qquad (2)$$

T = I-girder flange width, cm

P = designed vehicle wheel loads= 7,300 kg (HS20)
         =9,490 kg(HS20*1.3)
         = 11,620 kg(S112)

The designed slab dead load was assumed as 2.4 tons per m^3 for portland cement concrete as well as asphalt concrete. It was also assumed that the surface wearing coarse consists of 5 cm asphalt concrete. The total slab dead load can be easily obtained by multiplying the unit weight by the concrete volume. The bending moment due to designed dead load is calculated as following:

$$M_{D.L.} = 0.1 W_{D.L.} l^2 \qquad (3)$$

where

$M_{D.L.}$ = bending moment due to slab dead load, kg-cm

$W_{D.L}$ = designed slab dead load for the given thickness and one meter long slab, kg/cm

l = clear distance between I-girders plus slab thickness, cm

Slab steel design follows the Working Stress Design Method. The final design results for these three vehicle live load cases are shown in Figure 19. In this design the required minimum slab thickness is 17 cm, but the final selection of slab thickness should also consider the steel arrangement within the slab. Nevertheless, no matter how

thick the slab is , the required steel cross area (cm^2) for one meter long slab of S112 designed truck is much higher than those of HS20 and HS20 * 1.3. For instance, the required steel volume for S112 is 62% higher than that of HS20 and 28% higher than that of HS20* 1.3 for 23 cm slaab thickness case. It should be emphasized that it was the mean S112 vehicle gross weight selected in the case study, therefore, the design reliability in this case is only 50%. This result indicates that the bridge deck is substantially underdesigned under the current Bridge Design Specification even though the 30% vehicle overloading is considered. A close study is highly recommended in order to update the Bridge Design Specification.
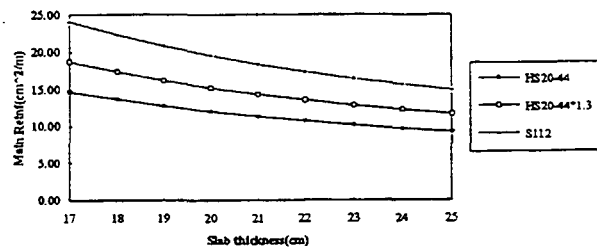

Figure 19 Slab steel design results from three different design vehicles

CONCLUSIONS

In this study, the collection of truck weights was conducted by installing the WIM equipments on National Freeways 1 and 3. From the analysis, it was concluded that the overloading situation is much more severe than which the official record shows and the pavement and bridge engineers' expectations. It can also be concluded that the WIM system can overcome the shortcomings of conventional static weight stations. The following conclusions have been drawn:

(1) The WIM equipment can be used efficiently to measure pavement and bridge related traffic factors such as weight information, number and type of axles, speed, and axle load ratios.

(2) The U11 and S112 are the two major truck types used on Taiwan's Freeway System, however, more than 90 percent of pavement damage comes from S112 which is less than 47 percent of the truck population on National Freeway 3.

(3) Not only the overloading rates of the single axle and tandem axle but also the TLF of the S122 is much lower than that of S112 at the same legal gross weight limit. It was concluded that S122 is much more efficient in load carrying than S112 and the gross weigh limits of these two trucks should be stipulated differently.

(4) The distributions and mean values of U11 vehicle gross weights are very compatible for both Freeways, but the average vehicle gross weight of S112 at National Freeway 3 is 8.3 tons higher than that of National Freeway 1. More than 84 % of the S112 of National Freeway 3 are overloaded, and the average vehicle gross weight is 40.4 tons. It is concluded that the same type of trucks but with different shipping freights resulted in different vehicle gross weight distributions and different axle load ratios.

(5) Due to the extraordinary overloading condition, the actual combined TLF is 2.7 times as large as the TLF predicted for the pavement design of National Freeway 3. The actual accumulated ESALs based on the WIM collection is 2.3 times as large as the predicted ESALs, and the difference is 5,572,000 ESALs for its first a year and seven months service life. This indicates that the pavement structure of the Freeway 3 is substantially underdesigned.

(6) The axle load ratios for U11 and S112 trucks obtained from this study are dramatically different from the standard vehicles recommended in the Standard Specification for Highway Bridge Design. A design case for bridge deck was studied; and it was concluded that the designed steel is around 28 percent less than what it should be when taking the HS20*1.3 instead of the S112 as the designed vehicle. This finding indicates that the current deck design of a simply supported bridge is undoubtedly underdesigned even though 30 percent of truck overloading was considered. Careful evaluation is highly recommended in order to update the design specification.

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