Characterizing the Load Spectra on a Rural Expressway in Binzhou, China: A Case Study

M. Robbins and D. Timm
Department of Civil Engineering, Auburn University, Auburn, Alabama, USA

ABSTRACT: Recently, China has experienced an increase in gross vehicle weights (GVW) due to rapid economic growth. Coupled with plans for extensive infrastructure expansion, the use of mechanistic-empirical (M-E) pavement design is necessitated. To meet these demands, it is essential to first characterize these extreme loads in the context of an M-E pavement design framework through load spectra. This case study documented the challenges in characterizing the unique axle configurations, heavy axle loads and traffic flow of Chinese vehicles for use in the M-E Pavement Design Guide (MEPDG). Traffic data were compiled from a weigh-in-motion (WIM) site on the Tianjing-Shantou Expressway, a connector between Beijing and Shanghai, near Binzhou (Shandong Province) from 2006-2007. This expressway experiences extremely heavy axle loads thought to be representative of typical expressway traffic. For example, a 90th percentile single axle load was 12.9 tons, nearly 1.75 times heavier than that on a rural representative interstate in the U.S. Although load limits are in place, it was found that they were frequently exceeded, with 31% of single axles and 56% of tandem axles exceeding the limits. The axle spacings and frequency of axle types observed from the WIM data varied significantly from axle configurations in the U.S., making it impossible to utilize the vehicle classes in the MEPDG. Additionally, the MEPDG requires only a single value to be entered for speed; however, large fluctuations in vehicle speed were observed among the Chinese vehicles. Using the MEPDG to assess the implications on required pavement thickness to mitigate pavement distress, it was found that the 10th percentile speed required an additional 28 cm of asphalt concrete over the thickness required for the average vehicle speed.

KEY WORDS: Load Spectra, Traffic, Load Distribution, Asphalt Pavements.

1 INTRODUCTION

Over the last few decades China has experienced rapid economic growth, accompanied by infrastructure expansion. China's expressway network is currently the second largest in the world with 2 million km of highway and since the year 2000 has been averaging a 20% expansion per year (KPMG 2009). This rapid growth has been followed by rapid pavement deterioration, such that in some provinces, pavement life-cycles range between two and three years before thorough rehabilitation is required (Hang et al. 2005). With an additional 1 million km of highway expected to be paved by the year 2020 (KPMG 2009), an effective and efficient pavement design method must be selected. One such method is mechanistic-empirical (M-E) pavement design.

Premature deterioration of China's roadways has been attributed to overwhelming traffic loads (Hang et al. 2005). It has been shown that unaccounted for overloading leads to underestimates of truck load factors and ultimately overestimates of expected pavement performance (Chia-pei 1998). Furthermore, it has been shown that in general, increasing axle weights by 30% can cut the predicted pavement life in half (Salem 2008).

Efforts have been made to quantify this overloading in Jiangsu Province, in which 30% of traffic was assumed to be large-sized freight vehicles overloaded by 30% (Liao et al. 2009). Engineers in the Anhui Province have assessed overloading as a function of the vehicle type, observing that three axle single unit trucks exceed the gross vehicle weight (GVW) legal limit more severely than other truck types (Hang et al. 2005).

To meet these growing demands it is vital to accurately characterize Chinese traffic within an M-E design framework. To do so, load spectra must be developed, as well as truck speed characterization. In an effort to complete the first step in accurately characterizing Chinese traffic, a sample of traffic data was collected from a weigh-in-motion (WIM) site on the Tianjing-Shantou Expressway near Binzhou in Shandong Province. This expressway, completed in 2007, serves as a connector between China's two largest cities, Beijing and Shanghai. Although this expressway connects two of the largest cities, the area through which it runs is mostly rural. It is expected to become one of the most heavily travelled expressways in China, with some of the highest axle loads (Timm et al. 2006).

2 SCOPE

This case study documents the characterization of traffic on a rural expressway in the Shandong province of China by utilizing data from a WIM station on the Tianjin-Shantou Expressway from a 16-month period. Axle groups were defined for the development of load spectra. Speed, GVW and axle type frequency were also assessed. Furthermore, comparisons were drawn with a rural highway near Shorter, Alabama, U.S. The implications on pavement thickness were evaluated using an M-E design system.

3 TRAFFIC CHARACTERIZATION

3.1 General Description of Chinese Traffic

Chinese tractors and trailers are mostly manufactured in China, and as a result Chinese vehicles do not fall into the traditional U.S. classifications for trucks. Rather, they fall under the Chinese vehicle classifications, where "S" represents a semi-tractor trailer and "U" represents a single unit truck. The number immediately following the letter designates the type of steer axle. The remaining numbers describe, sequentially, the remaining axles on the vehicle. A number one represents a single axle, a two represents a tandem axle, and lastly, a three represents a tridem axle group. Vehicle classes U2.1, U2.2, and S2.1.2 have been identified as vehicles in which the steer axle is immediately followed by another axle, thus resembling a tandem axle group. However, the tandem steer axle group is comprised of two single axles with single tires, rather than the traditional tandem axle commonly seen in the U.S.

3.2 Characterization of Traffic in Shandong

Data were collected from a WIM station on a four-lane divided highway near Binzhou, China in the Shandong province on the Tianjing-Shantou Expressway during a 16 month period, beginning in August 2006 and ending in December 2007. Distributions for GVW and speed were compiled as well as the frequency of axle types. Furthermore, traffic was characterized by axle group passes and associated load distribution. To do so, an axle group was defined as having axle spacing(s) of 1.37 m or less. Steer axles (single tires) were differentiated from single axles (dual tires) by categorizing the first axle on a vehicle as a steer axle, unless the subsequent axle spacing fell within the 1.37 m spacing, thus defining it as a tandem steer axle group. Only 2,693 of the approximately 1.5 million axles (0.17%) were identified as tandem steer axles and due to this negligible number these tandem steer axles could be considered traditional tandem axle groups for use in M-E design. The remaining axles were then assigned to an axle group (single, tandem, tridem, etc.) based on the 1.37-m axle spacing definition.

To put the traffic on the Tianjing-Shantou Expressway into context, comparisons were drawn with traffic on a rural 4-lane divided highway in the U.S. Traffic data were collected at a WIM station on I-85 near Shorter, Alabama. Statistics for GVW, axle type frequency and speed were determined in addition to load spectra, for comparison with the traffic in Shandong. Axles and associated weights were categorized into axle groups using the previously described 1.37-m axle spacing. The rural interstate in Alabama has been opened for a significantly longer duration than the newly constructed Tianjing-Shantou Expressway; consequently traffic volumes are higher and more stable. Therefore, for the WIM dataset from rural Alabama, a sample, representative of annual traffic on this rural interstate, was selected. This was done by randomly selecting four months of one full year (January 1, 2009-December 31, 2009) to analyze. The months selected included February, June, November and December.

3.3 Gross Vehicle Weights

Figure 1 illustrates the distribution of the GVW of vehicles from each WIM site with summary statistics inset. On average, the GVWs observed on the Shandong highway were 1.5 times heavier than those vehicles seen on the Alabama highway. The GVW legal limit in China is 40 metric tons for single-unit trucks, single-trailer trucks and multi-trailer trucks and 46 metric tons for single-trailer trucks carrying containers (Hang et al. 2005). Due to the difficulties in identifying these vehicles, the entire population of vehicles from the Shandong WIM station was used to assess overloading: 28.45% of all vehicles exceeded 40 metric tons and 15.76% exceeded 46 metric tons. Contrary to this, only a small percentage (2.8%) of vehicles surpassed the U.S. legal limit of 36.2 metric tons at the WIM station in Alabama. This confirms that overloading is a severe problem on the Tianjing-Shantou Expressway as observed on other highways in China (Hang et al. 2005).

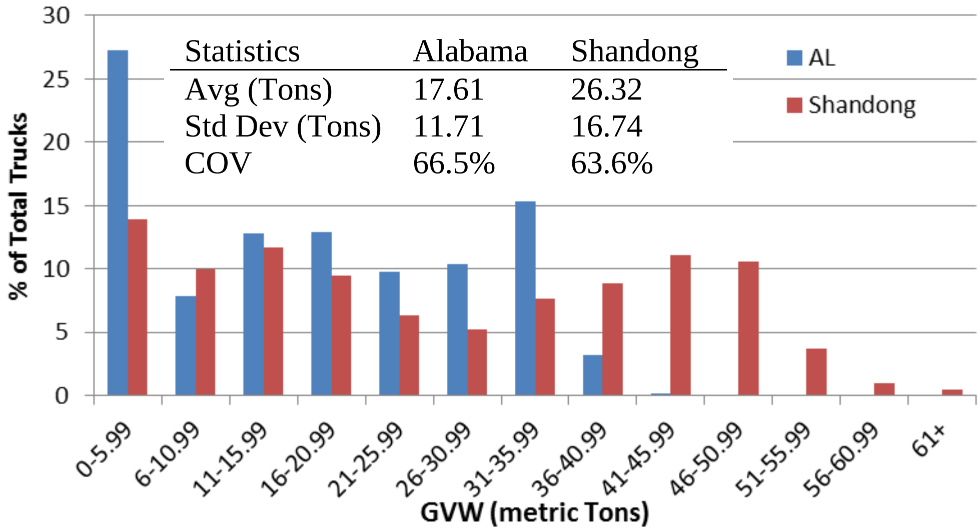

Figure 1: GVW histogram and summary statistics.

3.4 Axle Type Frequency

Chinese vehicle configurations are very different from those used in the U.S., exhibiting disproportionate frequencies of axle types relative to U.S. traffic. Figure 2 illustrates the difference in axle types between the two WIM stations. At both sites, axle groups of 5 axles or more were observed, but as shown in Figure 2, occurred very infrequently. Although the percentages of steer axles were nearly the same between the two sites, there was a much higher percentage of single axles (55.6%) on the Shandong expressway relative to the Alabama interstate (34.9%). As a result, the percentage of tandem axles was less than half of that seen at the U.S. site. This creates a much more severe loading scenario, as tandem axles distribute the load across a greater area of pavement than do single axles. Given the consistent overloading that is evident on this and other Chinese roadways (Hang et al. 2005) the disproportionate frequency of single axles to tandem axles is of concern for pavement design.

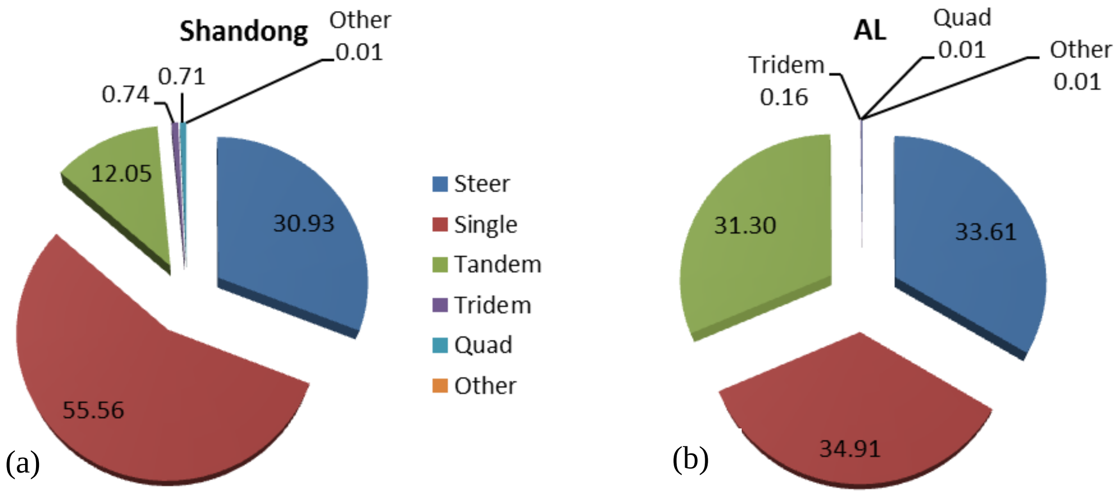

Figure 2: Axle type frequency for (a) Rural interstate in Shandong Province of China and (b) Rural interstate in Alabama.

3.5 Load Spectra

Cumulative distributions of axle group weights were developed for each dataset, as shown in Figures 3 and 4. Chinese legal limits were reported by Hang et al. (2005) as 6 metric tons for single axles with 2 tires (steer), 10 metric tons for single axles with 4 tires, 18 metric tons and 22 metric tons for tandem and tridem axles, respectively. Although tandem axles make up only 12% of all axles on this Shandong highway, more than 56% of those axles were found to exceed the legal limit. Tridem axles were the most frequently overloaded at 66% and single axles (4 tires) were overloaded at a frequency of 31%. Putting this in context of pavement design; applying the generalized fourth power rule for a tandem weight of 22.7 metric tons would result in 2.4 times as much damage as a tandem axle loaded to the Chinese legal limit of 18 metric tons. As illustrated in Figure 4, the legal limits in the U.S. for single and tandem axles are 9.1 metric tons and 15.4 metric tons, respectively. More than 98% of single axles on the Alabama interstate fell below 9.1 metric tons while 93% of tandems were below 15.4 metric tons. In general, the distributions of axle group weights on the Shandong expressway are much wider and heavier relative to its Alabama counterpart. For instance, the 90th percentile weight for a single axle found on the Shandong expressway was 75% heavier than that found on the Alabama interstate.

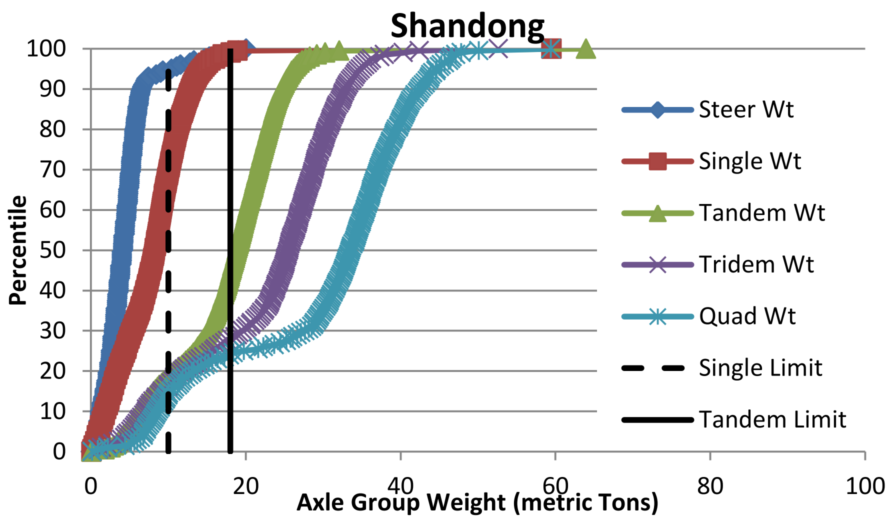

Figure 3: Cumulative distribution of axle group weights for Shandong.

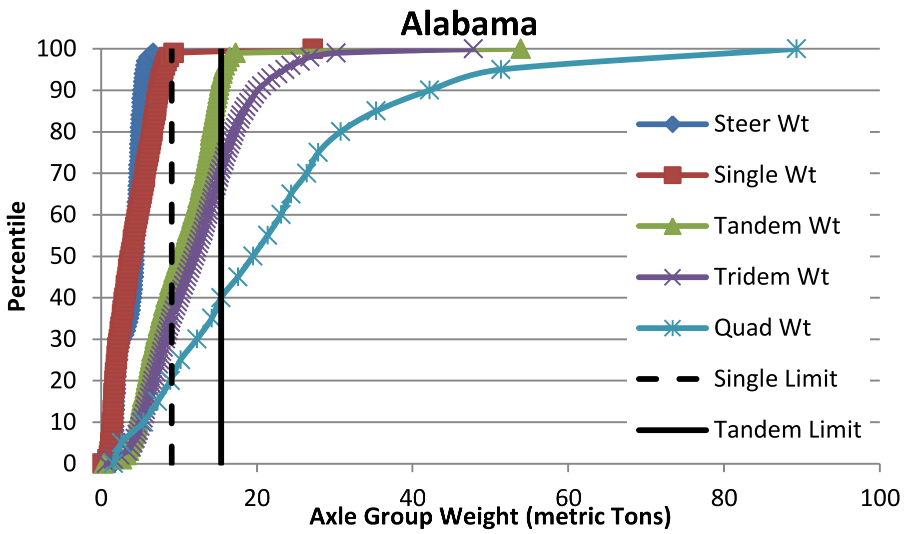

Figure 4: Cumulative distribution of axle group weights for Alabama.

3.6 Speed

Shown in Figure 5 are the distributions of vehicle speeds for both WIM sites. On average, the Shandong traffic traveled 42.6 km/h slower than the Alabama traffic, and was much more variable, evident by both the coefficient of variation (COV) and the shape of the distribution. The COV for the Shandong expressway was found to be 27.54%, which is significantly higher than that of the Alabama interstate. Furthermore, the middle of the Alabama speed distribution was much less variable than the Shandong distribution, with the majority (98.4%) of the speeds falling in the range of 86-135 km/h. On the other hand, the Shandong traffic covered a wider spread with 84.3% of speeds falling between 46 and 95 km/h. In M-E design vehicle speed is a critical factor as it, in part, dictates the modulus of the asphalt in a flexible pavement. However, it is generally considered a constant value. Given the large fluctuations in travel speed shown here and the well-known increase of critical strains in the pavement relative to decreases in speed (Chatti et al. 1996, Mateos and Snyder 2002, Robbins and Timm 2009), the entire distribution of speeds should be considered in analysis and design.

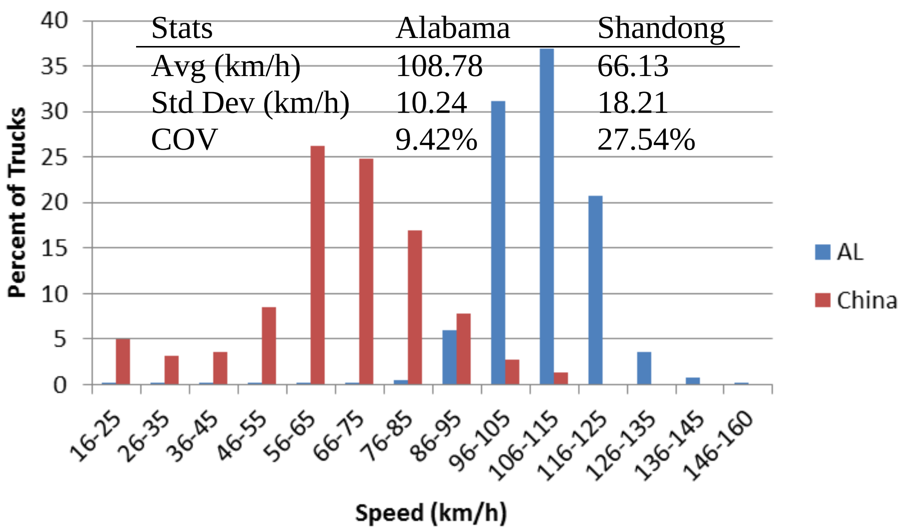

Figure 5: Speed histogram and summary statistics.

4 IMPLICATIONS ON DESIGN THICKNESS USING THE MEPDG

To determine the effect of overloaded traffic on pavement thickness, the Mechanistic-Empirical Pavement Design Guide (MEPDG), version 1.1, was utilized to conduct a 20-year, level 3 design with both sets of WIM data. Design parameters were held constant varying only the traffic to determine the effect on required thickness to prevent pavement distresses. The MEPDG default design thresholds for fatigue cracking (25% of lane area), total rut depth (19 mm) and IRI (2.7 m/km) were utilized.

A climate station in Montgomery, AL was selected given the close proximity 32 km southwest to the WIM station located in Shorter, AL. The similar latitudes of Montgomery, AL (32°21' N) and Binzhou (37°40' N) lead to similar climates. Furthermore, as required by the MEPDG, a depth to water table of 6.1 meters was entered for the climate station selected.

Typical pavement cross-sections for Shandong province could not be modeled within the confines of the MEPDG due to the extensive use of lime and fly ash stabilization in China for which the MEPDG has not been calibrated. As a result, it was elected to use a typical cross section used in Alabama. A level 3 design was executed, using rudimentary asphalt concrete properties that were consistent with typical Alabama mixtures, so that differences due to load spectra could be emphasized. A level 3 analysis was also selected for the base and subgrade materials. A 6-inch crushed stone base was specified with particle size distribution consistent with materials used in a typical Alabama pavement cross-section. With the exception of the particle size distribution, the default properties for crushed stone were utilized. An A-4 soil was selected for the subgrade material as well as all of the accompanying default values for that material.

The MEPDG requires traffic to be characterized on a per-vehicle basis from which axle types and weights are derived. For this analysis, traffic was characterized by passes of axle groups, so the vehicle classes within the MEPDG had to be altered to represent axle groups rather than vehicles as shown in Table 1. Steer axles were considered as single axles given that the MEPDG does not differentiate between the two types. The MEDPG cannot handle axle groups consisting of more than 4 axles. Therefore, the frequency and axle weight distributions of those axle groups consisting of more than 4 axles were redistributed among the remaining axle types by dividing them into tandem, tridem, and quad axle groups. For example, a vehicle with seven axles with consecutive spacing less than 1.37 m between axles was divided into a quad and a tridem axle.

Table 1: Representation of axle groups in MEPDG

Vehicle	Rep Axle	Adj Frequency %		Axles Per Truck			
Class	Group	AL	Shandong	Single	Tandem	Tridem	Quad
4	Steer	33.6	30.9	1	0	0	0
5	Single	34.9	55.5	1	0	0	0
6	Tandem	31.3	12.1	0	1	0	0
7	Tridem	0.2	0.8	0	0	1	0
8	Quad	0.0	0.7	0	0	0	1

The traffic volume was subsequently adjusted to reflect the increase in tandem, tridem and quad axles. However, the volumes for the two locations were based on different time periods. To draw direct comparisons among the predicted distresses, the traffic volumes were selected based on an equivalent total weight between the two locations. The average annual daily truck traffic (AADTT) for the WIM station in Alabama was computed by dividing the total number of axle group passes based on the adjusted frequencies in Table 1 by the number of days in the period (119 days). The total weight per day carried by all trucks was then determined for the WIM station in Alabama using the load spectra, the distribution of the axle groups and AADTT. Once computed, total weight per day for the Alabama station was then used in conjunction with the load spectra and the distribution of axle groups of the Shandong station, to calculate an equivalent AADTT. As a result, truck axle volume for Alabama was approximately 19,700 axles/day, whereas the volume for Shandong was approximately 14,600 axles/day, nearly 25% less than in Alabama. This was expected due to the heavier axle weights leading to fewer axles needed to carry the same total weight.

In addition to AADTT, the MEPDG required hourly and monthly distributions of traffic volume. The default hourly distribution was selected for both locations. The default monthly distributions in the MEPDG reflect no seasonal variations and therefore were selected. Zero traffic growth was also selected. Lastly, the default value speed (96.5 km/h) was initially selected to be consistent with typical highway speeds in the U.S.

4.1 Thickness Requirements

After adjustments had been made to the traffic volume to fit into the MEPDG framework, a 20 year design was completed. To do so, iterations were performed to determine the required thickness of the asphalt concrete layers necessary to prevent premature pavement distresses. The material properties and climate were identical among the two locations investigated, allowing the effect of the different traffic characteristics on pavement thickness to be assessed.

The thickness of the bottom AC lift was varied until predicted distresses fell below the acceptable limits for total rutting (19 mm), fatigue cracking (25% of lane area) and IRI (2.71 m/km). To meet all three design thresholds, a total AC thickness of 33 cm was required for the Alabama traffic data and 35.5 cm for the Shandong traffic, as shown in Table 2. Due to the more efficient load spectra on the Shandong highway, when total freight movement was held constant, only 2.5 additional centimeters of thickness were needed to meet the design thresholds. However, it would be expected that increased volume of these heavier axles would result in a more significant increase in thickness. This was investigated by applying the same traffic volume (that from Alabama) to both locations.

In varying the thickness for the Shandong section to meet design thresholds at the default speed and same traffic volume as in Alabama (rather than by the previous 14,600 axles/day determined by equivalent weight) it was found that rutting was the controlling distress. The threshold for IRI (2.71 m/km) was met with only 44.4 cm of total AC. Predicted rutting improved significantly with increased thickness, however beyond 35.5 cm of AC, very little improvement was found with increased thickness. In fact, 55.9 cm of AC was necessary to meet the 19 mm threshold for total rutting and was the resulting AC thickness required, a 57% increase over the 35.5 cm of AC required for the volume determined by equivalent weight. Given that the Shandong highway had recently opened at the time of the WIM station collection, it is likely that traffic volume will gradually increase over time as the remainder of the expressway downstream is completed. This analysis provides better insight into the seriousness of the heavily loaded axle passes and the extent to which these pavements must be built to prevent early distresses.

The analyses thus far assumed a constant speed of 96.5 km/h, however, traffic in Shandong was found to be much slower and more variable. Previous studies have shown that critical strains increase with a reduction of speed (Chatti et al. 1996, Mateos and Snyder 2002, Robbins and Timm 2009). Therefore, additional analyses were conducted at the average speed (Figure 5) at each location. The results of this analysis are shown in Table 2. By reducing the speed to the average speed in Shandong (66.1 km/h) it was found that a significantly thicker cross-section of 45.7 cm was required to meet distress thresholds. This is

10.2 centimeters thicker than the same analysis at 96.5 km/h, reiterating the importance of considering slow moving vehicles in pavement design. On the Alabama highway, the site average was slightly higher than the default speed, which did not affect the required thickness. Lastly, 96.5 km/h represents approximately the 10th percentile speed on the Alabama highway. Although using the 10th percentile speed may be considered conservative, this analysis showed at these higher speeds, the required design thickness was not as easily influenced. On the other hand, when the 10th percentile speed was much slower, as was the case in Shandong with a 10th percentile speed of 41.8 km/h, the effect on the design thickness was very large. As expected, a significant increase, nearly two-fold, over the pavement thickness at the default speed was necessary to meet the distress thresholds.

Table 2 Summary of design thickness for varying speeds

Location	Speed Category	Speed (km/h)	Total AC (cm)	Fatigue Cracking (% lane)	Total Rutting (mm)	IRI (m/km)
AL	Default/ 10th percentile	96.5	33	0.888	18.79	2.68
	Site Average	108.8	33	0.86	18.46	2.67
Shandong	10th percentile	41.8	73.6	0.0404	18.99	2.64
	Site Average	66.1	45.7	0.654	18.99	2.67
	Default	96.5	35.5	2.53	18.87	2.70
Shandong w/ AL volume	Default	96.5	55.9	0.239	18.99	2.65

5 CONCLUSIONS

Traffic on a rural highway in Shandong province of China was analyzed and compared with traffic from a rural highway in Alabama. Distributions of GVW, speed and axle type as well as the load spectra of each axle group were developed for both sites. From this case study, the key findings are as follows:

- As few as 28.45% and as many as 44.28% of all trucks exceeded the GVW limit on the Tianjing-Shantou Expressway near Binzhou, indicating a frequent overloading condition.
- Single axles are used more frequently on the Shandong expressway than on the Alabama interstate. Ideally, heavier restrictions should be placed on single axle weights. However, this may be an impractical solution. A more viable approach is to better understand the load distribution so that effective and efficient designs may be developed for these extremely heavy loads.
- Speed is a critical parameter in M-E pavement design and was found to heavily influence pavement design thickness, particularly for slower moving vehicles. Due to the large variability observed in the Shandong data, a speed distribution should be used rather than a constant velocity.
- Total rut depth was found to be the most critical distress due to the heavy axle loads at both locations.
- Using the equivalent total axle weight per day, additional AC was required to prevent predicted distresses in Shandong, likely due to heavier axle weights and increased use of single axles.

REFERENCES

Chatti K., Kim H.B., Yun K.K., Mahoney J.P., and Monismith C.L. (1996). *Field Investigations into Effects of Vehicle Speed and Tire Pressure on Asphalt Concrete Pavement Strains*. Transportation Research Record.1539, 66-71.

Chia-Pei J. C., Chung-Piau C. (1998). *Truck Load Distribution and Its Impact on Vehicle Weight Regulations in Taiwan*. Transportation Research Record 1501, 87-94.

KPMG (2009). *Infrastructure in China: Foundation for Growth*. <http://www.kpmg.com/CN/en/IssuesAndInsights/ArticlesPublications/Pages/Infrastructure-in-China-200909.aspx> (June 22, 2010).

Hang W., Li X., Ju P., He J. (2005). *Site Survey and Analysis of Highway Trucks Overloading Status Quo in Anhui*. Journal of the Eastern Asia Society for Transportation Studies, 6, 1790-1803.

Liao C., Zhang P., Wang J. (2009). *Discussion on Pavement Design for Different Lanes in Jiangsu Section of Hu-Ning Expressway Expansion Project*. Journal of Wuhan University of Technology, 33(6), 1228-1232.

Mateos A. and Snyder M.B. (2002). *Validation of Flexible Pavement Structural Response Model with Data from the Minnesota Road Research Project*. Transportation Research Record:1806, 19-29.

Robbins M., and Timm D. (2009). *An Investigation into Strain Pulse Duration on a Full Scale Instrumented Pavement*. Proceedings of the 88th Annual Meeting of the Transportation Research Board, Transportation Research Board, Washington D.C.

Salem H.M.A. (2008). *Effect of Excess Axle Weights on Pavement Life*. Emirates Journal for Engineering Research, 13(1), 21-28.

Timm D., Priest A., Yang Y., and Gao X. (2006). *Perpetual Pavements in China*. Hot Mix Asphalt Technology, 11(3), 14–19.