EFFECT OF MICHIGAN MULTI-AXLE TRUCKS ON PAVEMENT DISTRESS

Executive Summary

Karim Chatti, Ph.D.

Michigan State University
Department of Civil and Environmental Engineering
Pavement Research Center of Excellence

Final Report
Executive Summary
Project RC-1504

February 2009

EFFECT OF MICHIGAN MULTI-AXLE TRUCKS ON PAVEMENT DISTRESS

EXECUTIVE SUMMARY

Truck traffic is a major factor in pavement design because truck loads are the primary cause of pavement distresses. Trucks have different axle configurations that cause different levels of pavement damage. The American Association of State Highway Transportations Officials (AASHTO) pavement design procedure only accounts for single and tandem axles used in the AASHO road test and uses extrapolation to estimate the damage due to tridem axles. Truck axle configurations and weights have significantly changed since the AASHO road study was conducted in the late 1950's and early 1960's. There remain concerns about the effect of newer axle configurations on pavement damage, which are unaccounted for in the AASHTO procedure. The State of Michigan is unique in permitting several heavy truck axle configurations that are composed of up to 11 axles, sometimes with up to 8 axles within one axle group. Therefore, there is a need to quantify the relative pavement damage resulting from these multiple axle trucks. The objective of this research study is to determine the effect of heavy multi-axle Michigan trucks on pavement distress by quantifying the effects of trucks with different axle configurations (single, tandem and multi-axles) on pavement damage. This was done by determining Axle Factors (AF) from laboratory and mechanistic analyses and then calculating Truck Factors (TF) using these AF and the AASHTO Load Equivalency Factors (LEF).

For the purpose of this report, the definitions of AF, TF and LEF are as follows:

The Load Equivalency Factor (LEF) is defined as the relative damage of an axle group to that of the standard 18 kip single axle.

$$LEF = \frac{Damage\,(axle\ configuration)}{Damage\,(18\text{ - }kip\ standard\ axle)}$$

The Axle Factor (AF) is defined as the relative damage of an axle group to that of a single axle carrying a load equal to the gross axle group weight divided by the number of axles within the axle group. Effectively, the AF converts an axle group into an equivalent number of this single axle. For example, a 39-kip tridem AF is determined as:

$$AF_{39\text{-}kip\ tridem} = \frac{Damage\,(39\text{ - }kip\ tridem)}{Damage\,(13 - kip\ single)}$$

The Truck Factor (TF) is defined as the sum of the products of AF and the LEF of the corresponding single axle for each axle group within a given truck configuration. For example, the TF for a class 7 truck composed of a 15 kip steer axle and a 39-kip tridem axle is calculated as follows: TF = AF_{steer} * LEF_{steer} + AF_{tridem} * $LEF_{13\ kip\ single}$.

Volume I of this report includes background information, literature review and statistical analyses using truck traffic and pavement performance data from in-service pavements; Volume II contains the analyses pertaining to asphalt pavements, including laboratory fatigue and rut data, and mechanistic analysis; and Volume III contains the analyses pertaining to concrete pavements, including laboratory fatigue and joint deterioration data, and mechanistic analysis. Volumes II and III contain conclusions from each analysis and recommended truck factors for pavement design and truck weight and size policy for asphalt and concrete pavements, respectively.

The findings from the study are valuable for both truck weight and size policy purposes as well as pavement design protocols. The study provides updated truck factors taking into account multiple axle group effects and compatible with the AASHTO load equivalency framework for:

- Maximum legal loads for each truck type (useful for weight and size policy)
- Axle load spectra for each truck class (useful for pavement design)

ANALYSIS OF PERFORMANCE DATA FROM IN-SERVICE PAVEMENTS

The Michigan Department of Transportation (MDOT) has a very comprehensive pavement surface distress database. The data include Distress Index (DI), Ride Quality Index (RQI), Faulting and Rutting. A separate database contains traffic count and weight data. Therefore, as the first step these data were utilized to investigate the relative effect of Michigan multi-axle trucks on actual pavement damage. Because of colinearity in the data (since different truck configurations use the same road) several remedies were tried, and the most effective way was to group similar configurations together: 1) single-tandem, and 2) multiple axles/trucks. Trucks with single and tandem axles can be found in classes 5, 6, 8, 9, 10, 11 and 12 while trucks with multiple axles are in classes 7, 10 and 13. Several regression analyses were conducted including univariate, multiple and stepwise regression.

Analysis of In-service Flexible Pavement Performance Data

The following preliminary conclusions were drawn for the effect of heavy multiple axle trucks on flexible pavement damage:

1. Trucks with single and tandem axles affect pavement cracking (DI) more than those with multiple axles (tridem and higher).
2. Conversely, heavier trucks with multiple axles have more effect on rutting than those with single and tandem axles.
3. RQI results did not show enough evidence to draw a firm conclusion.

Analysis of In-service Rigid Pavement Performance Data

The following preliminary conclusions were drawn for the effect of heavy multiple axle trucks on rigid pavement damage:

1. Trucks with single and tandem axles affect pavement cracking (DI) more than those with multiple axles (tridem and higher).
2. Conversely, heavier trucks with multiple axles have more effect on roughness (RQI), which is an indirect measure of faulting, than those with single and tandem axles.

Recommendation for Further Analysis

The statistical analyses on in-service pavement performance data did not lead to definitive conclusions that can be implemented in a quantitative manner. Rather, they have highlighted general apparent trends that need to be confirmed with mechanistic analyses, controlled laboratory testing, or better yet, accelerated pavement testing (APT). Volumes II and III of this report contain details of laboratory and mechanistic analyses in support of the study objectives for flexible and rigid pavements, respectively. Full-scale accelerated pavement testing (APT) was outside the scope of this study. However, it is recommended that such tests be conducted in a future study. Since MDOT does not have an APT facility, it is recommended that MDOT consider joining other State Highway Agencies (SHA) in conducting a pooled fund study to support the findings of this study using full-scale APT tests.

LABORATORY AND MECHANISTIC ANALYSES

In addition to the investigation of in-service pavement traffic and distress data presented in volume I, the research problem was investigated using: 1) laboratory experimentation, and 2) mechanistic analysis. A brief description of each approach follows.

ASPHALT PAVEMENT ANALYSES

Laboratory Fatigue and Rut Testing of HMA Mixtures

The indirect tensile cyclic test with loading cycles that simulate different axle/truck configurations was used to examine their relative effect on fatigue cracking of an asphalt mixture. The unconfined compression cyclic load test with similar loading cycles was used to examine their relative effect on permanent deformation of an asphalt mixture. Five different axle configurations and five different truck configurations were studied. Based on the experimental results from fatigue and rut testing of asphalt concrete mixes using the indirect tensile cyclic load test and the uniaxial cyclic load test, respectively, the following main conclusions can be drawn:

1. Multiple axles were found to be less damaging in fatigue per load carried compared to single axles. Increasing the number of axles carrying the same load results in less fatigue damage. This decrease in fatigue damage was found to be more significant between single, tandem and tridem axles, while it starts to level off at higher axle numbers. Similar results were obtained for trucks where trucks having more axles and axle groups had lower truck factors per tonnage than those with single axles.
2. Rutting damage due to different axle configurations is approximately proportional to the number of axles within an axle group. In other words, rutting damage is proportional to the gross weight of the axle group or truck, with multiple axles causing slightly less damage than a combination of smaller axle groups, for the same load carried. This was due mainly to the effect of rest period between the axle load cycles.

Figure 1 summarizes the axle factors obtained from laboratory fatigue and rut testing of HMA mixtures and compares them to the AASHTO axle factors (extrapolated for axles larger than the tridem based on a best fit curve using the axle factors from single, tandem and tridem axles).

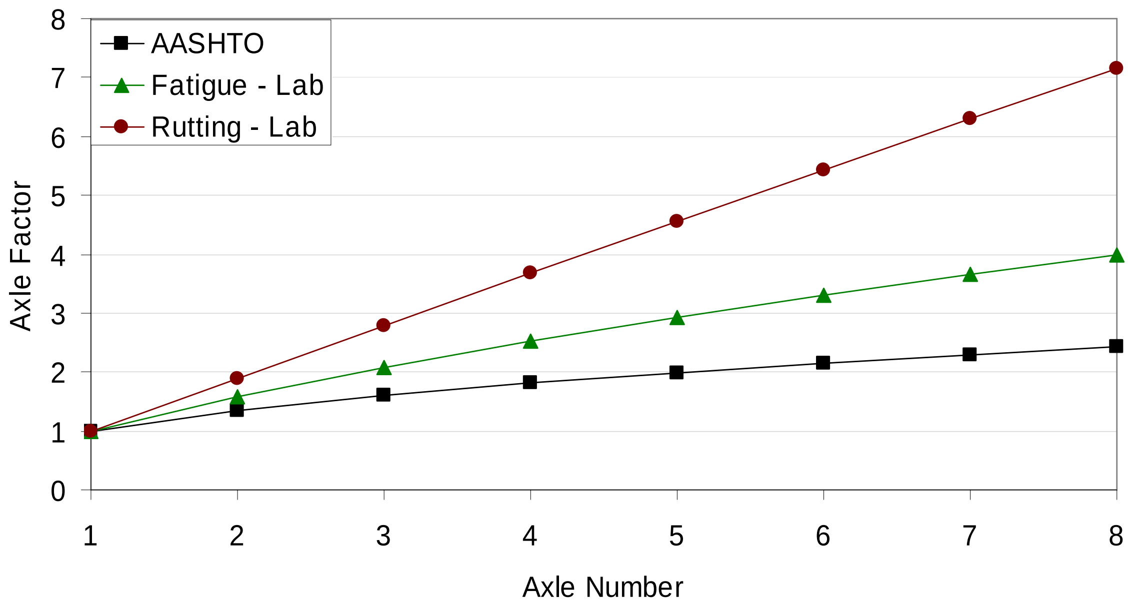


Figure 1 Flexible pavement axle factors for various axle configurations

Mechanistic Analyses of HMA Pavements

The mechanistic based computer programs SAPSI-M and KENPAVE were used to analyze the effect of multiple axles on fatigue and rutting, respectively, of different pavement structures. The SAPSI-M program was needed to calculate the dissipated energy density per cycle, which correlated best with fatigue failure under multiple axles. Also, the mechanistic-empirical rutting model (VESYS), calibrated using field data from the SPS-1 experiment, was used to predict the rutting in the various layers within the pavement structure. Results from mechanistic analyses confirm the experimental findings; i.e., that:

1. Multiple axles are less damaging in fatigue per load carried compared to single axles.
2. Rutting damage due to different axle configurations is approximately proportional to the number of axles within an axle group.

However, load equivalency factors (LEF) derived from mechanistic analyses can be significantly higher than those from AASHTO, with the differences being higher for thinner flexible pavements. These results suggest that the AASHTO based fourth power law may need to be revised in the future.

Recommendations

This study was charged with determining the relative damage caused by multiple axles within an axle group; i.e., how much damage is caused by grouping multiple axles into one axle group. The scope of the study did not include verifying the AASHTO's "Fourth Power" damage law; i.e., we were not charged with determining how much damage is caused by increasing the load of a given axle relative to the standard 18-kip single axle. To do so would require extensive full-scale testing similar to what had been done in the original AASHO road test. Therefore, the Truck Factors (TF) were obtained by converting multiple axle groups within each truck configuration into an equivalent number of single axles using the Axle Factors (AF) obtained in this study, calculating the LEF of each axle group by multiplying the AF values obtained from the laboratory with the Load Equivalency Factor (LEF) from AASHTO corresponding to the single axle at a given load, and then summing the LEF of the different axle groups within a truck. This was done for different pavement cross-sections varying in AC layer thickness and modulus.

Flexible Pavement Truck Factors Using Legal Load Limits for Weight and Size Policy

Tables 1 and 2 summarize recommended Truck Factors based on multiplying the axle factors for fatigue and rutting, respectively, by the AASHTO LEF value for a given legal load per axle (e.g., for a 39 kip tridem use 13 kip legal axle load). These truck factors are therefore based on fatigue and rutting considerations, but are provided within the AASHTO LEF framework.

Figures 2 and 3 show the same fatigue and rutting based Truck Factors for different pavement structures. Theses factors are ranked in descending order of relative damage caused to a flexible pavement with SN=5 (AC layer modulus of 350 ksi and thickness of 3.5 in) to better show the most/least damaging truck configurations.

Table 1 HMA Fatigue-based Truck Factors for Legal Load Limits - AASHTO LEF Framework

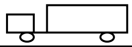
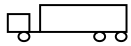
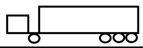
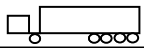
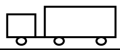
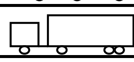
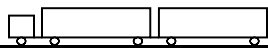
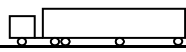
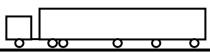
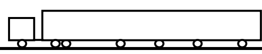
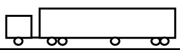
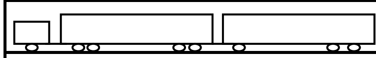
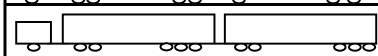
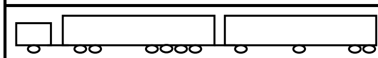
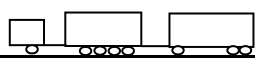
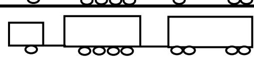
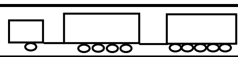
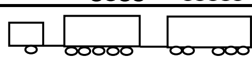
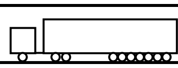
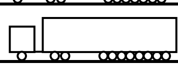
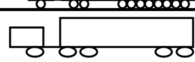
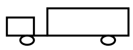
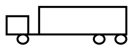
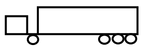
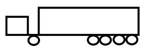
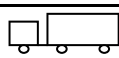
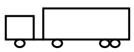
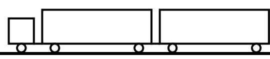
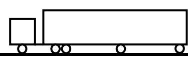
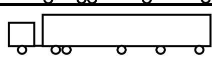
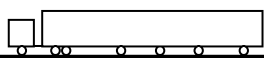
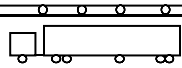
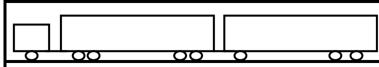
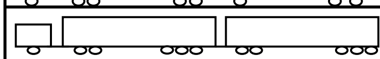
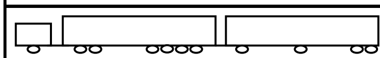
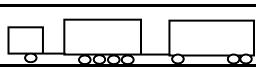
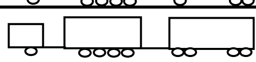
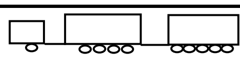
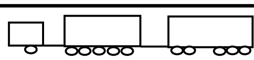
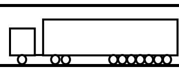
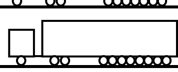
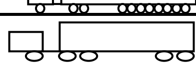
			Truck Factors					
			Eac = 350 ksi			Eac = 700 ksi		
Truck	Truck No.	Total Wt.	3.5 in	8 in	12 in	3.5 in	8 in	12 in
	1	*33.4*	1.533	1.507	1.499	1.524	1.501	1.497
	2	*47.4*	1.523	1.459	1.440	1.501	1.445	1.434
	3	*54.4*	1.082	1.009	0.989	1.057	0.995	0.983
	4	*67.4*	1.198	1.115	1.092	1.169	1.099	1.085
	5	*51.4*	2.533	2.507	2.499	2.524	2.501	2.497
	6	*65.4*	2.523	2.459	2.440	2.501	2.445	2.434
	7	*87.4*	4.533	4.507	4.499	4.524	4.501	4.497
	8	*83.4*	3.523	3.459	3.440	3.501	3.445	3.434
	9	*101.4*	4.523	4.459	4.440	4.501	4.445	4.434
	10	*119.4*	5.523	5.459	5.440	5.501	5.445	5.434
	11	*91.4*	2.942	2.843	2.815	2.908	2.823	2.805
	12	*117.4*	3.362	3.227	3.189	3.316	3.200	3.176
	13	*151.4*	3.041	2.848	2.795	2.974	2.810	2.777
	14	*161.4*	4.607	4.451	4.408	4.553	4.420	4.393
	15	*117.4*	3.188	3.067	3.034	3.146	3.043	3.022
	16	*125.4*	2.607	2.451	2.408	2.553	2.420	2.393
	17	*132.4*	1.969	1.821	1.781	1.917	1.792	1.767
	18	*143.4*	2.711	2.542	2.496	2.652	2.509	2.480
	19	*138.4*	2.487	2.341	2.300	2.436	2.312	2.287
	20	*151.4*	2.576	2.423	2.380	2.523	2.392	2.366
	21	*79.4*	2.513	2.411	2.381	2.479	2.390	2.371

Table 2 HMA Rutting-based Truck Factors for Legal Load Limits - AASHTO LEF Framework

			Truck Factors					
			Eac = 350 ksi			Eac = 700 ksi		
Truck	Truck No.	Total Wt.	3.5 in	8 in	12 in	3.5 in	8 in	12 in
	1	*33.4*	1.533	1.507	1.499	1.524	1.501	1.497
	2	*47.4*	1.734	1.663	1.642	1.710	1.648	1.634
	3	*54.4*	1.279	1.189	1.165	1.248	1.172	1.157
	4	*67.4*	1.529	1.418	1.388	1.490	1.396	1.378
	5	*51.4*	2.533	2.507	2.499	2.524	2.501	2.497
	6	*65.4*	2.734	2.663	2.642	2.710	2.648	2.634
	7	*87.4*	4.533	4.507	4.499	4.524	4.501	4.497
	8	*83.4*	3.734	3.663	3.642	3.710	3.648	3.634
	9	*101.4*	4.734	4.663	4.642	4.710	4.648	4.634
	10	*119.4*	5.734	5.663	5.642	5.710	5.648	5.634
	11	*91.4*	3.244	3.129	3.096	3.205	3.105	3.085
	12	*117.4*	3.754	3.595	3.551	3.699	3.563	3.536
	13	*151.4*	3.737	3.494	3.428	3.652	3.446	3.405
	14	*161.4*	5.240	5.040	4.985	5.171	5.001	4.966
	15	*117.4*	3.731	3.574	3.530	3.677	3.543	3.516
	16	*125.4*	3.240	3.040	2.985	3.171	3.001	2.966
	17	*132.4*	2.747	2.532	2.475	2.672	2.491	2.455
	18	*143.4*	3.335	3.123	3.064	3.261	3.081	3.045
	19	*138.4*	3.384	3.172	3.114	3.311	3.130	3.094
	20	*151.4*	3.595	3.365	3.302	3.515	3.320	3.280
	21	*79.4*	2.936	2.819	2.784	2.897	2.794	2.772

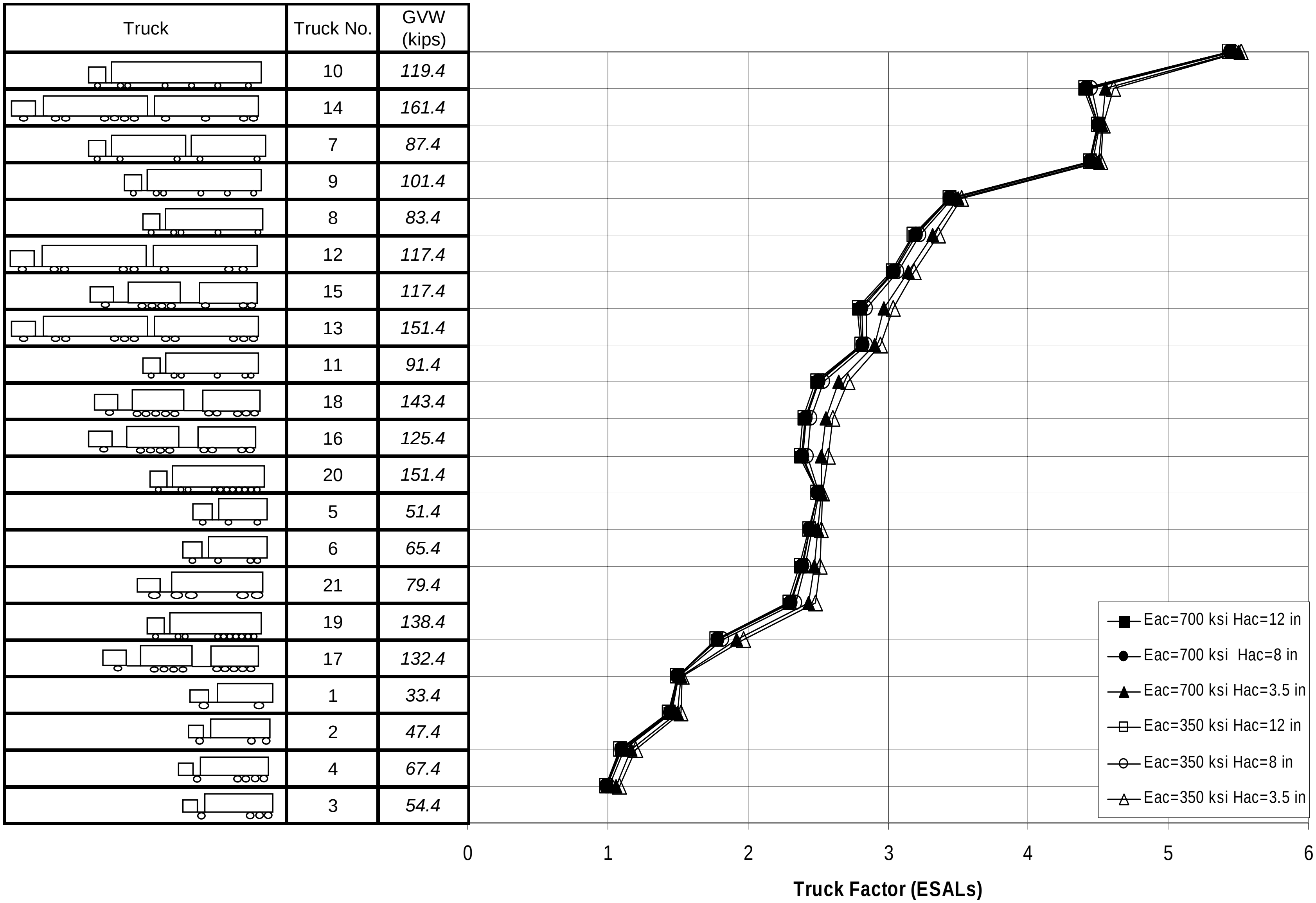


Figure 2 Fatigue-based Truck Factors within AASHTO LEF framework

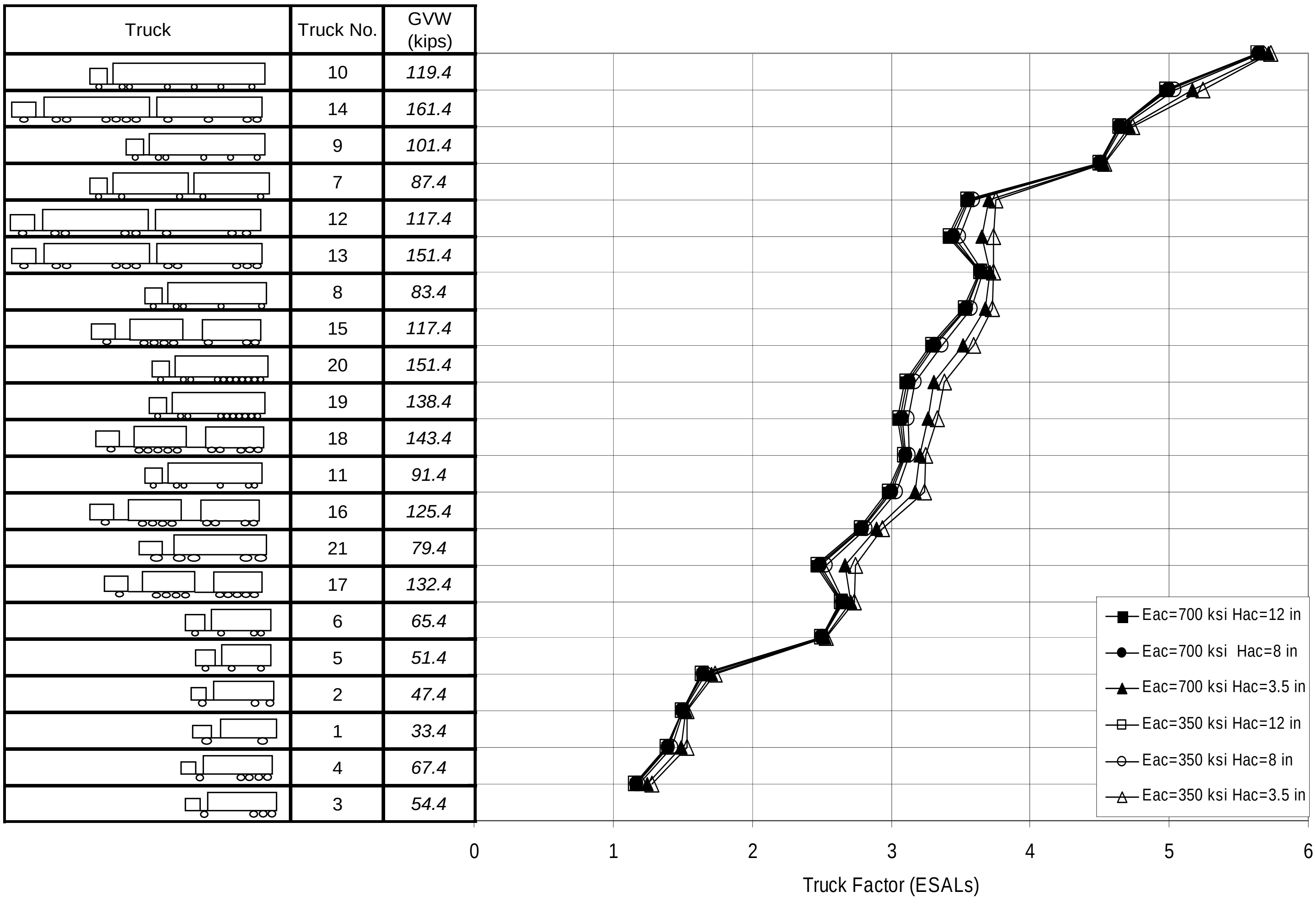


Figure 3 Rutting-based Truck Factors within AASHTO LEF framework

Truck Factors Using Axle Load Spectra for Flexible Pavement Design

The truck factors (TF) presented above were calculated using the legal load limits for all the axles and trucks. However, not all the trucks using the roadways are always fully loaded. These truck factors could prove to be very conservative from a design point of view. Therefore, truck factors should also be calculated considering actual loads carried by the trucks in Michigan. Weigh-in-motion (WIM) data were collected from 42 weigh stations in Michigan for the year 2007. The data from these weigh stations were used to determine the axle load spectra for different classes of trucks. The load spectra were then averaged to calculate the truck factor for each truck class. A similar procedure was used for calculating truck factors as was described above, for fatigue cracking and rutting respectively, except that the entire load spectrum for each axle group and each truck class was considered to calculate the truck factor. The procedure used to calculate TF's is summarized as follows:

(1) Convert multiple axle groups within each truck configuration into an equivalent number of single axles using the Axle Factors (AF) as defined in this study.
(2) Calculate the Load Equivalency Factor (LEF) of each axle group by multiplying the AF values obtained from the laboratory with the LEF from AASHTO corresponding to the load carried by an individual axle within each load category of a given axle group (e.g., 10 kip for an individual axle of a 30 kip tridem).
(3) Sum the LEF of the different axle groups within a truck.

Tables 3 and.4 summarize recommended Truck Factors based on multiplying the axle factors for fatigue and rutting, respectively, by the AASHTO LEF value using the axle load spectra from 42 WIM stations in Michigan. These truck factors are therefore useful for pavement design, taking into account fatigue and rutting considerations, and are provided within the AASHTO LEF framework. Table 5 and Figure 4 compare the TFs from this study to those currently used by MDOT.

Table 3. Fatigue-based Truck Factors for Flexible Pavement Design - AASHTO LEF Framework

	Truck Factors - Fatigue (AASHTO Framework)					
	Eac=350ksi			Eac=700ksi		
Truck Class	3.5 in (SN=5.02)	8 in (SN=6.83)	12 in (SN=8.44)	3.5 in (SN=5.45)	8 in (SN=7.8)	12 in (SN=9.89)
5	0.196	0.188	0.186	0.193	0.186	0.185
6	0.525	0.499	0.492	0.516	0.494	0.490
7	0.666	0.634	0.626	0.654	0.628	0.623
8	0.420	0.401	0.396	0.413	0.397	0.394
9	0.874	0.831	0.819	0.858	0.823	0.816
10	1.437	1.372	1.356	1.414	1.360	1.350
11	1.138	1.092	1.080	1.122	1.084	1.077
12	1.126	1.106	1.104	1.118	1.104	1.103
13	1.696	1.608	1.585	1.665	1.591	1.577

Table 4. Rut-based Truck Factors for Flexible Pavement Design - AASHTO LEF Framework

	Truck Factors - Rutting (AASHTO Framework)					
	Eac=350ksi			Eac=700ksi		
Truck	3.5 in	8 in	12 in	3.5 in	8 in	12 in
5	0.197	0.188	0.186	0.193	0.187	0.186
6	0.589	0.560	0.552	0.578	0.554	0.549
7	0.795	0.752	0.741	0.779	0.744	0.738
8	0.433	0.412	0.407	0.425	0.408	0.405
9	1.019	0.969	0.956	1.001	0.960	0.952
10	1.776	1.691	1.669	1.746	1.675	1.661
11	1.141	1.095	1.083	1.124	1.086	1.079
12	1.132	1.112	1.109	1.124	1.110	1.108
13	2.096	1.985	1.956	2.057	1.964	1.946

Table 5. Comparison of Truck Factors for Flexible Pavement Design

Flexible Pavement with SN = 5

Truck Class	Truck Factors		
	Fatigue Cracking	Rutting	MDOT
5	0.196	0.197	0.1881
6	0.525	0.589	0.3710
7	0.666	0.795	0.8047
8	0.420	0.433	0.6092
9	0.874	1.019	0.7705
10	1.437	1.776	1.4640
11	1.138	1.141	1.5254
12	1.126	1.132	1.0410
13	1.696	2.096	1.5819

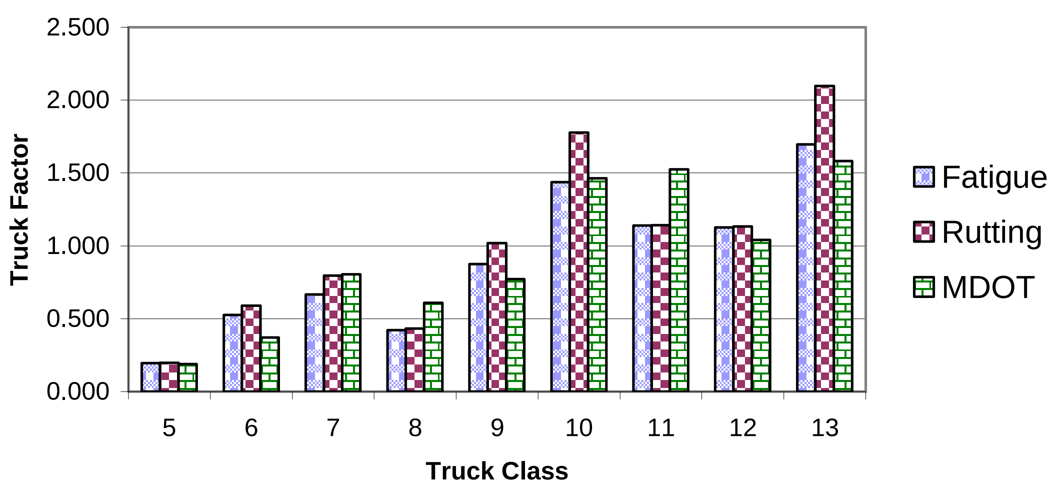


Figure 4. Comparison of current MDOT truck factors with those from this study for flexible pavement with SN = 5

CONCRETE PAVEMENT ANALYSES

Laboratory PCC Fatigue and Joint Deterioration Testing

Four-point flexural fatigue tests were conducted on 4” x 4” x 24” beams to study the effect of fatigue cracking in PCC. Six different axle configurations were studied. A 55 kip MTS hydraulic actuator was used for the fatigue tests. Additionally, a 5’ x 14’ unreinforced concrete slab was used to study the performance of aggregate interlock under repetitive loading using two stationary 11 kip hydraulic actuators placed on either side of the joint. An out of phase loading sequence between each stationary actuator simulated the moving wheel load of a truck.

Based on the experimental results from flexural fatigue testing of concrete beams using cyclic multiple pulse loading, the following main conclusions can be drawn:

1. Multiple axles were found to be less damaging in fatigue per load carried compared to single axles. Increasing the number of axles carrying the same load results in less fatigue damage.
2. If one takes into consideration the stress reduction due to the interaction between axles within the same axle group, then the fatigue damage caused by multiple axles groups becomes even lower by a significant amount.

The full-scale joint deterioration testing was inconclusive due to the fact that it was not possible to accelerate joint deterioration within the constraints of the laboratory setting (slab geometry, load configuration and foundation support). Several attempts were made to allow for accelerating damage at the joint; however, these attempts were unsuccessful. A small scale beam test with a double crack was proposed as an alternative to the full-scale slab test. However, there was not sufficient time and resources to conduct a series of multiple pulses that simulate the different axle configurations. Nonetheless, full-scale slab testing as well small-scale double crack beam testing will be conducted beyond the completion of the current study. Based on the mechanistic analysis, it is expected that multiple axles will be more damaging in faulting than single axles. However, this needs to be confirmed using the aforementioned laboratory tests.

Mechanistic analysis

Two mechanistic based computer programs, DYNASLAB and KENSLAB, were used to analyze the effect of multiple axles on different pavement structures. For concrete fatigue and joint faulting, six different axle configurations were analyzed. The stress and displacement time history for each axle configuration was obtained and used in the flexural fatigue and full scale lab tests. Results from mechanistic analyses confirm the experimental findings; i.e., that:

1. Multiple axles are less damaging in fatigue per load carried compared to single axles.
2. Faulting damage due to different axle configurations is approximately proportional to the number of axles within an axle group, with multiple axles causing slightly more damage than a combination of smaller axle groups, for the same load carried.

Load equivalency factors (LEF) derived from mechanistic analyses for fatigue can be significantly lower than those from AASHTO, while those for faulting can be significantly higher than those from AASHTO. These results suggest that the AASHTO based fourth power law may need to be revised in the future.

Figure 5 summarizes the axle factors obtained from laboratory fatigue testing, and mechanistic-based fatigue and faulting analyses, and compares them to the AASHTO axle factors. AASHTO axle factors have been extrapolated for axles larger than the tridem based on a best fit curve using the axle factors from single, tandem and tridem axles.

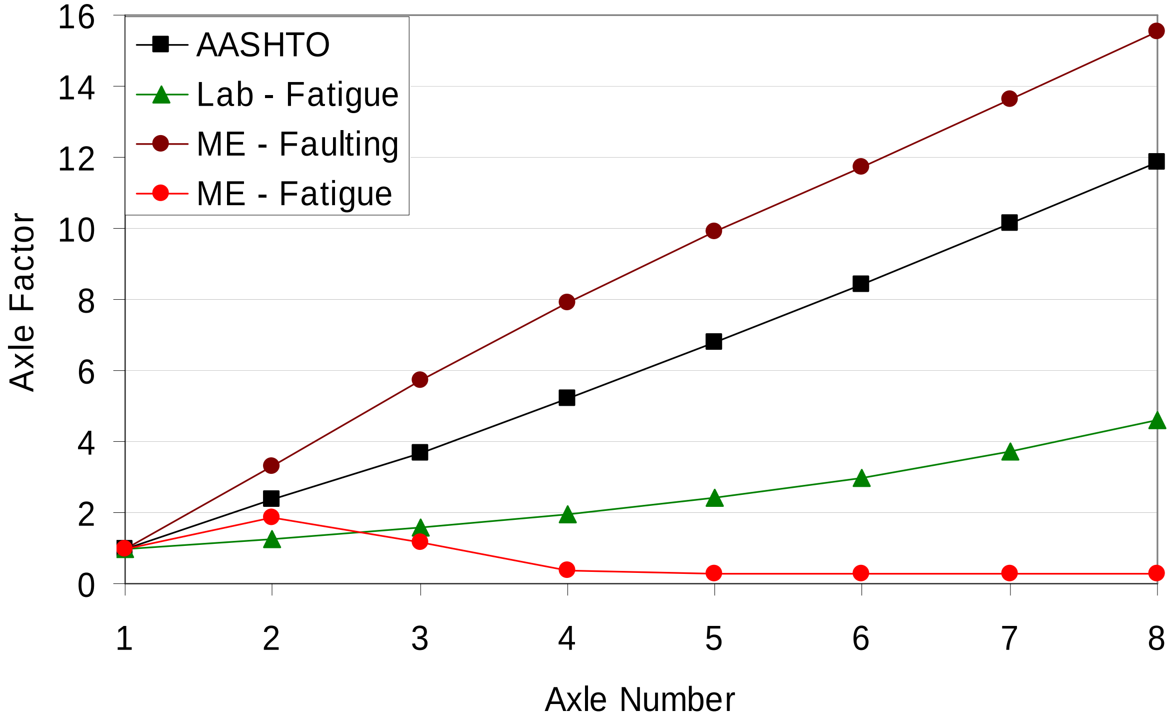


Figure 5. Rigid pavement axle factors for various axle configurations

Recommendations

This study was charged with determining the relative damage caused by multiple axles within an axle group; i.e., how much damage is caused by grouping multiple axles into one axle group. The scope of the study did not include verifying the AASHTO's "Fourth Power" damage law; i.e., we were not charged with determining how much damage is caused by increasing the load of a given axle relative to the standard 18-kip single axle. To do so would require extensive full-scale testing similar to what had been done in the original AASHO road test. Therefore, the TF's were obtained by converting multiple axle groups within each truck configuration into an equivalent number of single axles using the AF's obtained in this study, calculating the LEF of each axle group by multiplying the AF values obtained from the laboratory (fatigue) and mechanistic analysis (faulting) with the Load Equivalency Factor (LEF) from AASHTO corresponding to the single axle at a given load, and then summing the LEF of the different axle groups within a truck. This was done for different slab thicknesses.

Rigid Pavement Truck Factors Using Legal Load Limits for Weight and Size Policy

Tables 6 and 7 summarize recommended Truck Factors based on multiplying the axle factors for fatigue (laboratory) and faulting (mechanistic), respectively, by the AASHTO LEF value for a given legal load per axle (e.g., for a 39 kip tridem use 13 kip legal axle load). These truck factors are therefore based on fatigue and faulting considerations, but are provided within the AASHTO LEF framework.

Figures 6 and 7 show the same fatigue and faulting based Truck Factors for different slab thicknesses. Theses factors are ranked in descending order of relative damage caused to the pavement with slab thickness of 10 in to better show the most/least damaging truck configurations.

Table 6 Fatigue-based Truck Factors within AASHTO LEF Framework

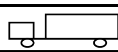
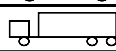
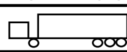
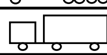
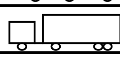
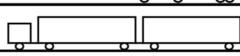
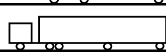
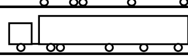
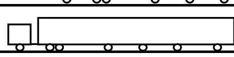
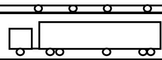
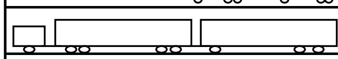
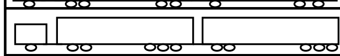
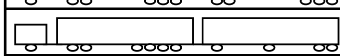
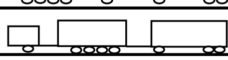
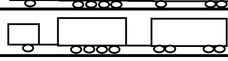
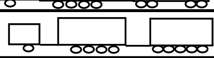
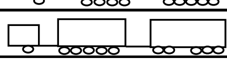
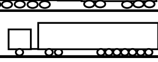
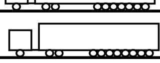
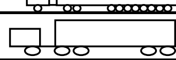
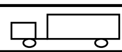
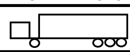
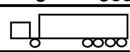
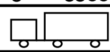
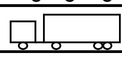
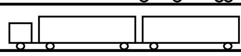
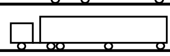
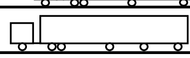
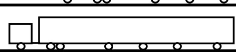
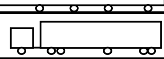
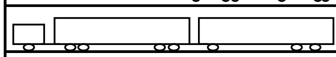
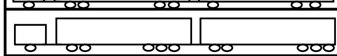
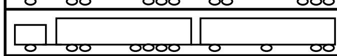
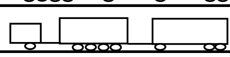
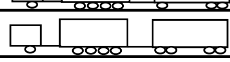
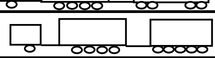
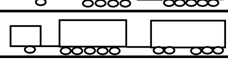
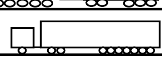
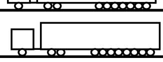
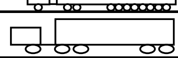
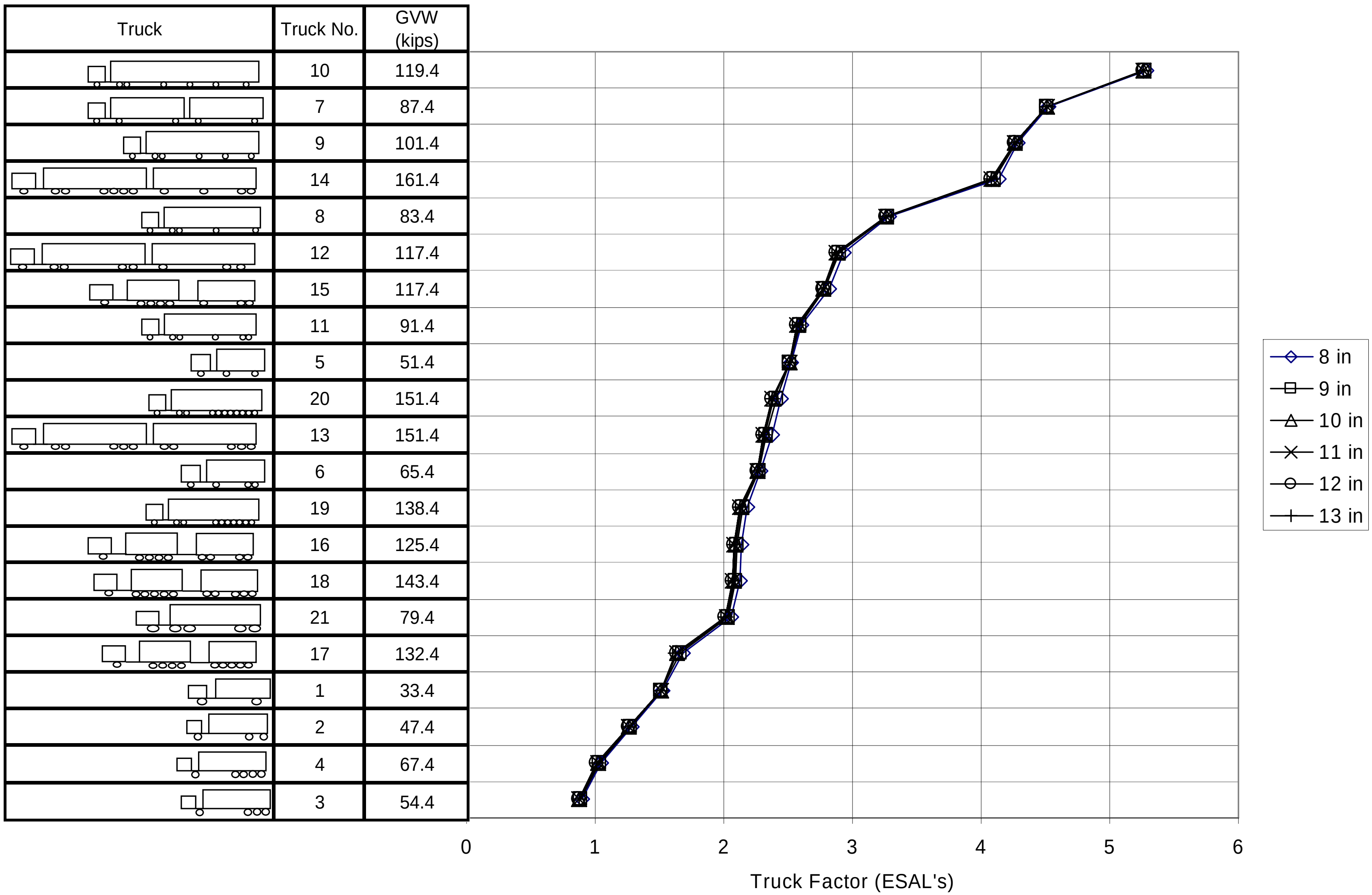
			Truck Factors - Fatigue (AASHTO Framework)					
			Slab thickness, D (in)					
Truck	Truck No.	Total Wt. (kips)	8	9	10	11	12	13
	1	33.4	1.519	1.512	1.509	1.508	1.507	1.507
	2	47.4	1.288	1.273	1.266	1.263	1.262	1.261
	3	54.4	0.902	0.887	0.881	0.878	0.876	0.876
	4	67.4	1.046	1.028	1.021	1.017	1.016	1.015
	5	51.4	2.519	2.512	2.509	2.508	2.507	2.507
	6	65.4	2.288	2.273	2.266	2.263	2.262	2.261
	7	87.4	4.519	4.512	4.509	4.508	4.507	4.507
	8	83.4	3.288	3.273	3.266	3.263	3.262	3.261
	9	101.4	4.288	4.273	4.266	4.263	4.262	4.261
	10	119.4	5.288	5.273	5.266	5.263	5.262	5.261
	11	91.4	2.607	2.586	2.576	2.572	2.570	2.569
	12	117.4	2.927	2.898	2.886	2.880	2.878	2.877
	13	151.4	2.372	2.335	2.319	2.311	2.308	2.306
	14	161.4	4.134	4.102	4.087	4.081	4.078	4.077
	15	117.4	2.815	2.789	2.778	2.773	2.770	2.769
	16	125.4	2.134	2.102	2.087	2.081	2.078	2.077
	17	132.4	1.685	1.654	1.640	1.634	1.632	1.630
	18	143.4	2.121	2.089	2.074	2.068	2.065	2.064
	19	138.4	2.180	2.146	2.132	2.125	2.122	2.121
	20	151.4	2.443	2.404	2.387	2.380	2.376	2.375
	21	79.4	2.057	2.034	2.023	2.019	2.016	2.015

Table 7 Faulting-based Truck Factors within AASHTO LEF Framework

Truck	Truck No.	Total Wt. (kips)	Truck Factors - Faulting (AASHTO Framework) Slab thickness, D (in): 8	9	10	11	12	13
	1	33.4	1.519	1.512	1.509	1.508	1.507	1.507
	2	47.4	2.527	2.499	2.486	2.480	2.477	2.476
	3	54.4	1.971	1.934	1.918	1.911	1.908	1.906
	4	67.4	2.518	2.470	2.449	2.440	2.436	2.434
	5	51.4	2.519	2.512	2.509	2.508	2.507	2.507
	6	65.4	3.527	3.499	3.486	3.480	3.477	3.476
	7	87.4	4.519	4.512	4.509	4.508	4.507	4.507
	8	83.4	4.527	4.499	4.486	4.480	4.477	4.476
	9	101.4	5.527	5.499	5.486	5.480	5.477	5.476
	10	119.4	6.527	6.499	6.486	6.480	6.477	6.476
	11	91.4	4.360	4.315	4.295	4.286	4.282	4.280
	12	117.4	5.194	5.131	5.104	5.091	5.086	5.083
	13	151.4	6.264	6.158	6.112	6.092	6.083	6.078
	14	161.4	7.359	7.272	7.234	7.218	7.210	7.206
	15	117.4	5.526	5.456	5.426	5.412	5.406	5.403
	16	125.4	5.359	5.272	5.234	5.218	5.210	5.206
	17	132.4	5.023	4.924	4.881	4.862	4.853	4.849
	18	143.4	5.608	5.515	5.475	5.457	5.448	5.444
	19	138.4	5.977	5.878	5.834	5.815	5.806	5.802
	20	151.4	6.466	6.357	6.309	6.288	6.278	6.273
	21	79.4	4.534	4.485	4.462	4.452	4.448	4.445



Truck No.	GVW (kips)
10	119.4
7	87.4
9	101.4
14	161.4
8	83.4
12	117.4
15	117.4
11	91.4
5	51.4
20	151.4
13	151.4
6	65.4
19	138.4
16	125.4
18	143.4
21	79.4
17	132.4
1	33.4
2	47.4
4	67.4
3	54.4

Figure 6 Fatigue-based Truck Factors within AASHTO LEF framework

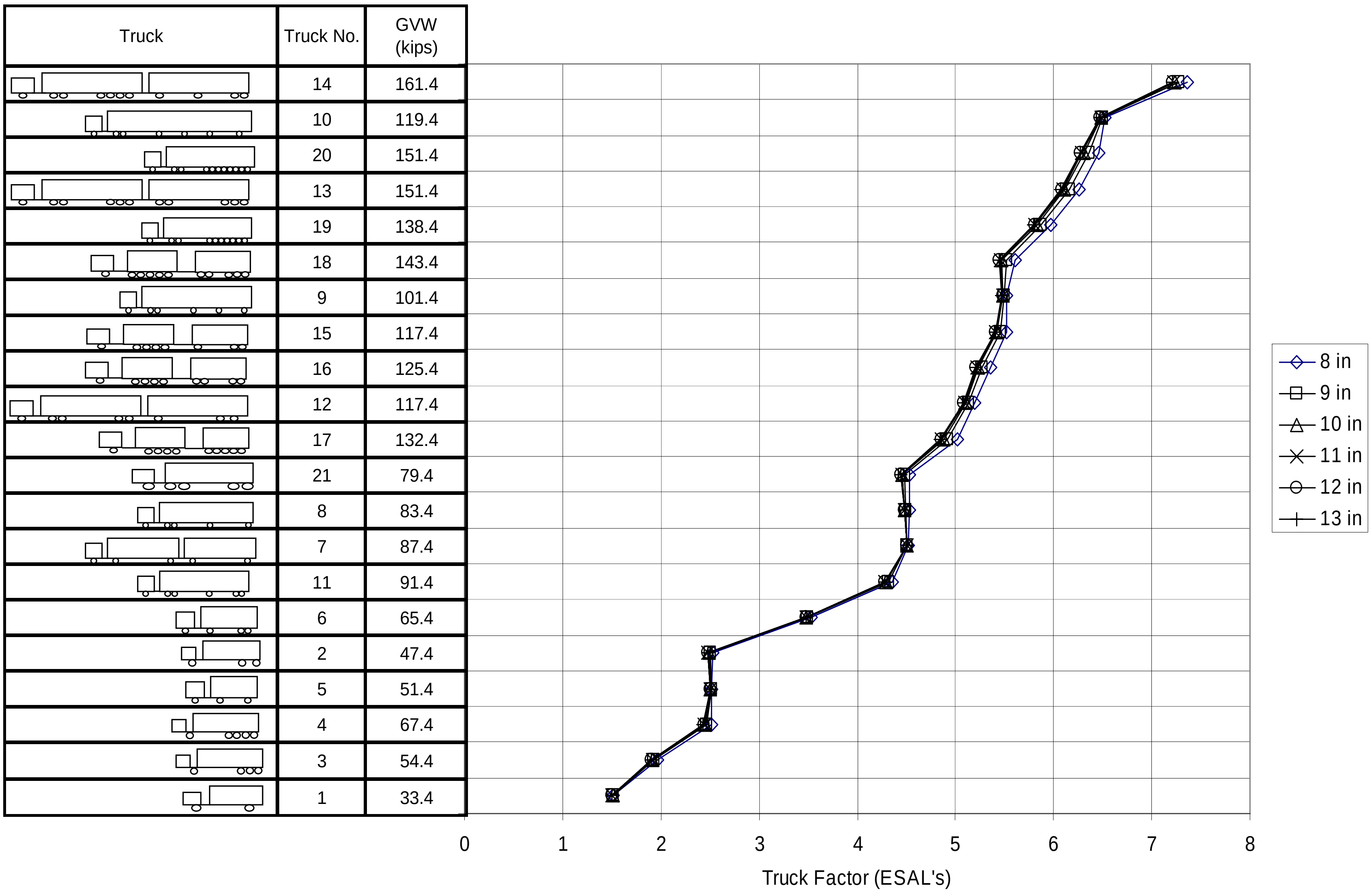


Figure 7. Faulting-based Truck Factors within AASHTO LEF framework

Truck Factors Using Axle Load Spectra for Rigid Pavement Design

The truck factors (TF) presented above were calculated using the legal load limits for all the axles and trucks. However, not all the trucks using the roadways are always fully loaded. These truck factors could prove to be very conservative from a design point of view. Therefore, truck factors should also be calculated considering actual loads carried by the trucks in Michigan. Weigh-in-motion (WIM) data was collected from 42 weigh stations in Michigan for the year 2007. The data from these weigh stations were used to determine the axle load spectra for different classes of trucks. The load spectra were then averaged to calculate the truck factor for each truck class. A similar procedure was used for calculating truck factors as was described above, for fatigue cracking and faulting respectively, except that the entire load spectrum for each axle group and each truck class was considered to calculate the truck factor. The procedure used to calculate TF's is summarized as follows:

(1) Convert multiple axle groups within each truck configuration into an equivalent number of single axles using the Axle Factors (AF) as defined in this study.
(2) Calculate the Load Equivalency Factor (LEF) of each axle group by multiplying the AF values obtained from the laboratory (fatigue) and mechanistic analysis (faulting) with the LEF from AASHTO corresponding to the load carried by an individual axle within each load category of a given axle group (e.g., 10 kip for an individual axle of a 30 kip tridem).
(3) Sum the LEF of the different axle groups within a truck.

Tables 8 and 9 summarize recommended Truck Factors based on multiplying the axle factors for fatigue cracking and faulting, respectively, by the AASHTO LEF value using the axle load spectra from 42 WIM stations in Michigan. These truck factors are therefore useful for pavement design, taking into account fatigue and faultiing considerations, and are provided within the AASHTO LEF framework. Table 10 and figure 8 compare the TFs from this study to those currently used by MDOT.

Table 8. Fatigue-based Truck Factors for Rigid Pavement Design - AASHTO LEF Framework

	Truck Factors - Fatigue (AASHTO Framework)					
	Slab thickness, D (in)					
Truck Class	8 in	9 in	10 in	11 in	12 in	13 in
5	0.193	0.191	0.190	0.190	0.190	0.190
6	0.455	0.449	0.446	0.445	0.445	0.445
7	0.579	0.572	0.570	0.569	0.569	0.568
8	0.402	0.397	0.396	0.395	0.395	0.394
9	0.719	0.710	0.706	0.704	0.703	0.703
10	1.325	1.309	1.303	1.300	1.298	1.298
11	1.117	1.106	1.101	1.099	1.099	1.098
12	1.113	1.110	1.110	1.111	1.111	1.111
13	1.396	1.376	1.368	1.364	1.363	1.362

Table 9. Faulting-based Truck Factors for Rigid Pavement Design - AASHTO LEF Framework

	Truck Factors - Faulting (AASHTO Framework)					
	Slab thickness, D (in)					
Truck	8 in	9 in	10 in	11 in	12 in	13 in
5	0.193	0.191	0.190	0.190	0.190	0.190
6	0.816	0.805	0.801	0.799	0.798	0.798
7	1.229	1.209	1.200	1.197	1.195	1.194
8	0.467	0.462	0.459	0.458	0.458	0.458
9	1.550	1.531	1.523	1.519	1.517	1.517
10	2.788	2.750	2.733	2.726	2.723	2.721
11	1.117	1.106	1.101	1.099	1.099	1.098
12	1.133	1.130	1.130	1.130	1.130	1.130
13	3.456	3.405	3.383	3.373	3.368	3.366

Table 10. Comparison of Truck Factors for Rigid Pavement Design

Rigid Pavement (D = 9 in.)

Truck Class	Truck Factors		
	Fatigue Cracking	Faulting	MDOT
5	0.191	0.191	0.1895
6	0.449	0.805	0.5854
7	0.572	1.209	1.3111
8	0.397	0.462	0.6759
9	0.710	1.531	1.2736
10	1.309	2.750	2.1806
11	1.106	1.106	1.604
12	1.110	1.130	1.2039
13	1.376	3.405	2.0837

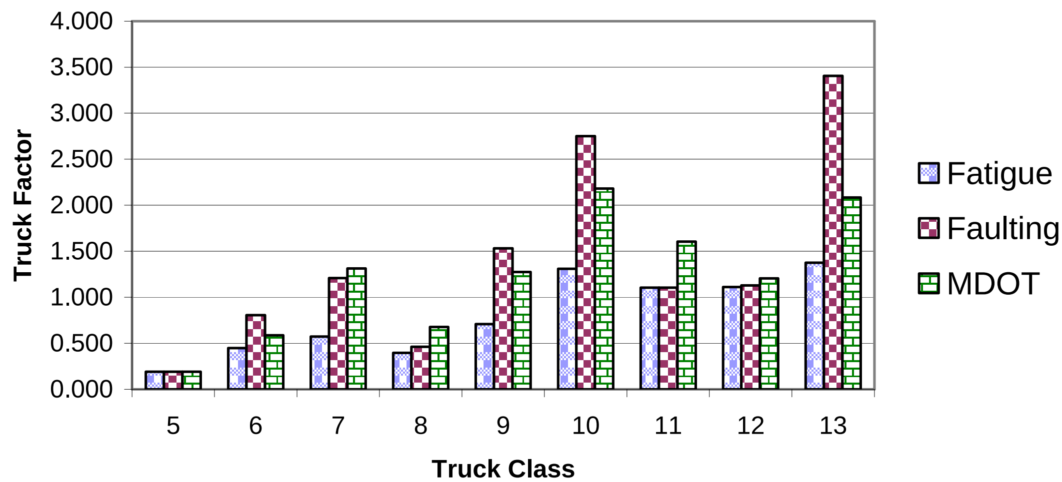


Figure 8. Comparison of current MDOT truck factors with those from this study for 9 inch slab