

Effect of Traffic Load Characterization (ESAL versus Axle load Spectra) on Rigid Pavement Performance

Syed Waqar Haider¹, Neeraj Buch², and Karim Chatti³

Abstract

Traffic is a significant factor in the pavement design process. Traffic characterization includes both the load magnitude and the number of load repetitions for each axle configuration. The two procedures for characterizing traffic in pavement design include: (a) fixed vehicle/axle, and (b) variable traffic and vehicle/axle. The concept of equivalent single axle load (ESAL) was developed in the AASHTO design guide while mechanistic-empirical design method, including the new M-E PDG, uses axle load spectra (ALS) to characterize traffic loadings and repetitions. The main objective of the paper is to assess the effects of different load characterizations (ESAL versus ALS) on rigid pavement performance. This is accomplished by characterizing axle load spectra as a bimodal mixture distribution and then using its parameters to estimate ESALs. Two specific aspects of this study are to: (a) evaluate the effect of equivalent ALS—different axle load spectra which are equivalent in ESALs on predicted rigid pavement performance; and (b) assess the effect of different axle load spectra on pavement performance by varying the number of repetitions to achieve the same ESALs. The results show that assuming axle load spectra which are not site-specific and achieving the desired level of ESALs by changing the number of repetitions may not give reliable estimates of expected pavement performance as compared to site-specific axle load spectra.

Introduction and Background

In the pavement design process, traffic characterization includes both the load magnitude and the number of load repetitions for each axle configuration. Historically, three different procedures for characterizing traffic have been used in the pavement design process: (a) fixed traffic, (b) fixed vehicle, and (c) variable traffic and vehicle (Huang 2004). For fixed traffic, the pavement thickness design is based on a single-wheel load, and the number of repetitions is not considered. Multiple wheels are converted to an equivalent single-wheel load (ESWL) for design. Typically, the heaviest wheel load expected on a pavement is used for design purposes. This method has been most frequently used for airport or highway pavements with heavy wheel loads but low repetitions. On the other hand, in the fixed vehicle/axle procedure, the thickness design is based on the number of repetitions of a standard vehicle or axle load, usually the 18-kip single axle load. If the axle load is different from 18-kip or consists of tandem or tridem axles, it must be converted to 18-kip single axle repetitions by an equivalent axle load factor (EALF). The number

¹Assistant Professor, Department of Civil and Environmental Engineering, Michigan State University, 3546 Engineering Building, East Lansing, MI-48824; PH (517) 353-9782; FAX (517) 432-1827; email: syedwaqa@egr.msu.edu

²Professor and Chairperson, Department of Civil and Environmental Engineering, Michigan State University, 3546 Engineering Building, East Lansing, MI-48824.

³Professor, Department of Civil and Environmental Engineering, Michigan State University, 3546 Engineering Building, East Lansing, MI-48824.

of repetitions for each axle type—single, tandem or tridem, are multiplied by EALF to obtain the equivalent effect based on an 18-kip single axle load. The summation of the equivalent effects of all axle loads during the design period results in an equivalent single-axle load (ESAL)—a single traffic parameter for design purposes. Lastly, for variable traffic and vehicles, both axles and their repetitions are considered individually. The loads are divided into a number of groups, and pavement responses (stresses, strains, and deflections) under each load group are determined separately and used to determine cumulative damage. The cumulative damage is subsequently related to pavement distresses (cracking, faulting, and rutting, etc.).

In mechanistic pavement analysis and design methods, it is not necessary to apply the load equivalency concept because different loads can be considered separately in the design process. The concept of load equivalency has been used often in the empirical methods for pavement design (e.g., AASHTO). In the AASHTO Guide for design of pavement structures, a mixed traffic stream of different axle loads and configurations is converted into a design traffic number by converting each expected axle load into an equivalent number of 18-kip single-axle loads, known as equivalent single-axle loads (ESALs). Load equivalency factors (LEFs) are used to determine the number of ESALs for each axle load and axle configuration. These factors are based on the present serviceability index concept and depend on the pavement type and structure. From the rigid pavements at the AASHTO Road Test (Huang 2004), Equations (1) through (3) were used to calculate the equivalent axle load factors (EALF):

$$\log \left(\frac{W_{tx}}{W_{t18} \beta} \right) = 4.62 \log(18+1) - 4.62 \log(L_x - L_2) + 3.28 \log(L_2) + \frac{G_t}{x} - \frac{G_t}{18} \quad (1)$$

$$G_t = \log \left(\frac{4.5 - p_t}{4.5 - 1.5} \right) \quad (2)$$

$$\beta_x = 1.00 + \frac{3.63(L_x + L_2)^{5.2}}{(D+1)^{8.46} L_2^{3.52}}$$

Where

W_{tx} = Number of x -axle load applications at the end of time t

W_{t18} = Number of 18-kip (80 kN) single-axle load applications at the end of time t

L_x = Load in kips on one single, one set of tandem or one set of tridem axles

L_2 = Axle code, 1= single, 2= tandem and 3= tridem

p_t = Terminal serviceability (i.e., pavement condition at failure)

SN = Structural number, $SN = a_1 D_1 + a_2 D_2 m_2 + a_3 D_3 m_3$

D = Slab thickness, inches

β_{18} = The value of β_x when $L_x = 18$ and $L_2 = 1$

$$EALF = \left(\frac{W_{t18}}{W_{tx}} \right) \quad (3)$$

The load equivalency factor is defined as the number of applications of the standard load of magnitude 18-kip (for single axle), which is equivalent in destructive effect to one application of load of different magnitudes (Deacon 1969). While pavements are subjected to a diverse and almost unlimited spectrum of load levels, the analysis of these complex loadings is facilitated by expressing the destructive effects of all loads in terms of an equivalent number of applications of a standard

load. Accordingly, the composite destructive effects of all loads, ESALs can be determined through:

$$ESAL = \sum_{i=1}^m EALF_i n_i \quad (4)$$

Where

- m = The number of axle groups
- $EALF_i$ = The equivalent axle load factor (EALF) for the i^{th} -axle load group
- n_i = The numbers of passes of the i^{th} -axle load group

It should be recognized that the AASHTO load equivalency factors were empirically derived using statistical analysis of the observed data. In addition, no effort was made to distinguish between different modes of distress—the equivalency factors were related only to performance as measured by the present serviceability index (PSI) (Carey Jr. and Irick 1960). Several studies have been conducted to determine and compare the load equivalency concept using mechanistic analyses where pavement responses could be utilized (Deacon 1969; Deacon and Deen 1969; Huang 1969; Ioannides et al. 1998). The major advantage of these approaches includes the determination of load equivalencies for other types of distresses (e.g., cracking and rutting in flexible pavements). The use of performance models incorporating critical pavement response for a specific distress to determine load equivalency established the power law. For example, Deacon (Deacon 1969) used a fatigue model developed in the laboratory to determine load equivalencies and compared the theoretically determined equivalent axle load factors (EALF) with the AASHTO EALF. Equation (5) presents the definition of EALF while Equation (6) shows the EALF for a standard axle in terms of the number of repetitions to failure:

$$EALF_{18} = \frac{\text{damage by X kip axle}}{\text{damage by 18 kip axle}} \quad (5)$$

$$EALF_s = \frac{\frac{1}{N_{fx}}}{\frac{1}{N_{fs}}} = \frac{N_{fs}}{N_{fx}} \quad (6)$$

Where

- $EALF_s$ = Equivalent axle load factor in terms of a standard axle
- N_{fs} = The numbers of repetitions of the *standard-axle* load
- N_{fx} = The numbers of repetitions of the *x-axle* load

The number of repetitions to failure can be determined from a transfer function. For example, the number of repetitions to fatigue failure for a particular strain level under a load can be expressed by (Huang 2004):

$$N_f = k \left(\frac{1}{\varepsilon} \right)^n \quad (7)$$

where

- N_f = The numbers of repetitions of a load to failure
- ε = The strain level due to a load
- k, n = Regression constants

Combining Equations (6) and (7), the power law can be generalized as:

$$EALF = \left(\frac{\varepsilon_x}{\varepsilon_s} \right)^n \quad (8)$$

Where

ε_x = The strain level due to application of a load

ε_s = The strain level due to the standard load

n = Exponent or power

It can also be assumed that for linear elastic material behavior the pavement response (in terms of stress or strain) is directly proportional to axle load (Huang 2004).

Therefore, pavement response can be replaced by axle load yielding:

$$EALF = \left(\frac{w_i}{w_s} \right)^n \quad (9)$$

Where

w_i = The load in kN on an axle group

w_s = The load in kN corresponding to the *EALF*

It was established through the AASHO Road Test that the impact of each individual axle load on flexible and rigid pavements can be approximately estimated according to the fourth power law (AASHTO 1993; Huang 2004). The fourth power law implies that pavement damage by passing axles increases exponentially with the increase of their load. The damage is related to loss in pavement serviceability. Therefore, to simulate AASHTO ESALs, an exponent value of four ($n = 4$) is used in this evaluation.

Axle load spectra have been used to develop the mechanistic-empirical pavement design guide (M-E PDG) instead of ESAL. Use of these load distributions provides a more direct and rational approach for the analysis and design of pavement structures to estimate the effects of actual traffic on pavement response and distress. In the M-E PDG, the traffic data required are the same regardless of the pavement type (i.e. flexible or rigid) or design type (new or rehabilitation) (NCHRP Project 1-37A 2004). Agencies typically collect three types of traffic data—weigh-in-motion (WIM), automatic vehicle classification (AVC), and vehicle counts. These data can be augmented by traffic estimates computed using traffic forecasting and trip generation models. WIM data are typically reported in a format similar to the FHWA W-4 Truck Weight Tables. AVC data are reported as the number of vehicles by vehicle type counted over a period of time, while vehicle counts are reported as the number of vehicles counted over a period of time. The normalized axle load distribution or spectra can only be determined from WIM data. Therefore, the level of input depends on the data source (site, regional, or national). For this design procedure, load spectra are normalized on an annual basis because no systematic or significant year-to-year or month-to-month differences were found in the analysis of the LTPP WIM data.

For highway pavements, the use of two types of load characterizations (equivalent axle load versus axle load spectra) in mechanistic analysis and design procedures need to be evaluated. It should be noted that traffic can be considered in terms of ESALs in mechanistic design procedure by considering a standard axle (18 kip) instead of an axle load distribution.

Problem Statement

The objective of this evaluation is to assess the effects of different load characterization (ESAL versus ALS) on pavement performance. This is accomplished by characterizing axle load spectra as a bimodal mixture distribution and then using its parameters to estimate ESALs. Two specific aspects of this study are to: (a) evaluate the effect of equivalent ALS—different axle load spectra which are equivalent in ESALs on predicted pavement performance; and (b) assess the effect of different axle load spectra on pavement performance by varying the number of repetitions to achieve the same ESALs.

Equivalent Axle Load Spectra

While pavement damage is inherently incorporated in the ESAL concept, it is of more practical use to relate axle load spectra and ESAL to determine the magnitude of traffic level. The fourth power law implies that pavement damage by passing axles increases exponentially with the increase in loads. Equation (9) presents the fourth power law in terms of EALF, where n is equal to 4. Combining Equations (4) and (9), the load-pavement impact based on axle load spectra can be obtained by integrating the contributions from all the loads x_i in the axle load distribution. A closed-form solution for estimating the ESALs from a continuous axle load distribution were obtained (Haider et al. 2008; Haider et al. 2009):

$$ESAL_j = \frac{N_j}{x_s^4} \left[3p_1\sigma_1^4 + 6p_1\mu_1^2\sigma_1^2 + p_1\mu_1^4 + 3p_2\sigma_2^4 + 6p_2\mu_2^2\sigma_2^2 + p_2\mu_2^4 \right] \quad (10)$$

There are two important components in Equation(10). The first component is the number of repetitions of an axle type and the second constituent is the loading characteristics. Both aspects are considered separately while designing pavements. Loading characteristics of an axle load spectra in terms of ESALs can be used to compare spectra at different sites. This also means that a site with a low frequency of axle loads may have more pavement damage due to higher loading characteristics or vice versa. To extract only loading contributions of an axle load distribution, Equation (10) can be reduced to a load spectra factor (ζ) if the total numbers of axle repetitions are reduced to one (Haider et al. 2008):

$$\zeta_j = \frac{1}{x_s^4} \left[3p_1\sigma_1^4 + 6p_1\mu_1^2\sigma_1^2 + p_1\mu_1^4 + 3p_2\sigma_2^4 + 6p_2\mu_2^2\sigma_2^2 + p_2\mu_2^4 \right] \quad (11)$$

Where

$$\zeta_j = \begin{array}{l} \text{Load spectra factor for the } j^{\text{th}} \text{ axle configuration (i.e., equivalent average} \\ \text{ESALs per repetition of the axle load spectra)} \end{array}$$

ζ_j represents the equivalent pavement damage in terms of ESALs by one pass of the j^{th} axle load. This simple statistic can be used to compare relative damage effects of different axle load spectra. The closed-form relationship between ESAL and axle load spectra was used to determine equivalent axle load spectra. These calculations are presented next.

ALS with equivalent ESALs. The closed-form solution shown by Equation (10) can be used to generate equivalent axle load spectra. The equivalent axle load spectra as defined in this study are the load distributions with different characteristics but having the same ESALs. Based on the assumption of a bimodal normal mixture model, three

such axle load spectra were generated as shown in Table 1. For example, Equations (12) and (13) present the calculation for the first load distribution.

$$ESAL_j = \frac{1 \times 10^6}{148^4} \left[\frac{3(0.3)(20)^4 + 6(0.3)(80)^2(20)^2 + (0.3)(80)^4}{3(0.7)(47.2)^4 + 6(0.7)(140)^2(47.2)^2 + (0.7)(140)^4} \right] = 1 \times 10^6 \quad (12)$$

$$\xi_j = \frac{1}{148^4} \left[\frac{3(0.3)(20)^4 + 6(0.3)(80)^2(20)^2 + (0.3)(80)^4}{3(0.7)(47.2)^4 + 6(0.7)(140)^2(47.2)^2 + (0.7)(140)^4} \right] = 1 \quad (13)$$

It can be seen from Table 1 that the three ALS considered have different characteristics (means and standard deviations of empty and loaded distributions), but have the same number of ESALs.

Table 1. Characteristics of axle load spectra with similar ESALs

ALS No.	Load Spectra Characteristics							ESALs
	μ_1	μ_2	σ_1	σ_2	P_1	N	X_s	
1	80	140	20	47.2	0.30	1,000,000	148	1.E+06
2	90	150	20	32.1	0.30	1,000,000	148	1.E+06
3	100	158	20	7.7	0.30	1,000,000	148	1.E+06

Figure 1 shows the plot of the generated equivalent axle load spectra. It should be noted that these load spectra were generated for a tandem axle configuration. Equation (10) also implies that there is another way of generating axle load spectra which have similar ESALs. One can achieve different ESALs by changing the repetitions (N).

Equivalent ESALs for different ALS. For different axle load distributions, the ESALs can be matched by changing N . For example, the number of repetitions can be calculated to match 1 million ESAL for a given loading characteristics. Equation (14) presents a sample calculation.

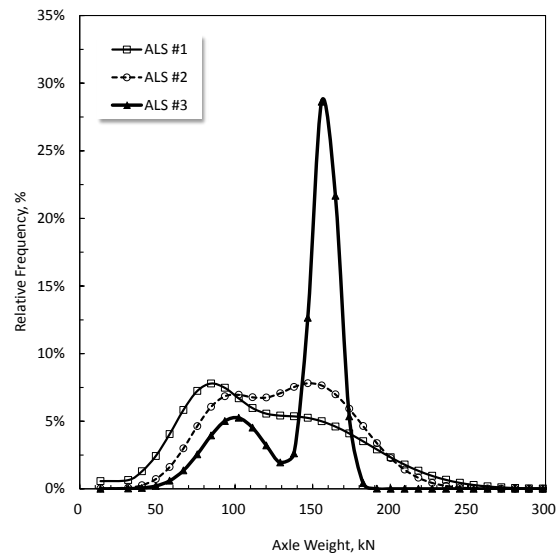
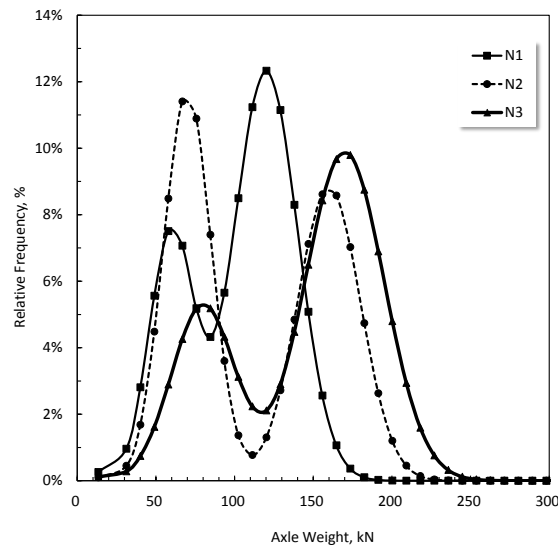
$$1 \times 10^6 = \frac{N}{148^4} \left[\frac{3(0.3)(14)^4 + 6(0.3)(60)^2(14)^2 + (0.3)(60)^4}{3(0.7)(20)^4 + 6(0.7)(120)^2(20)^2 + (0.7)(20)^4} \right] \quad (14)$$

$N = 2,743,626$

Table 2 shows the loading characteristics and required number of repetitions for three tandem axle load spectra considered in this study. In terms of ADTT, the heavier loading will need less repetitions to reach a given number of ESALs. Thus, ALS #1 will have the highest ADTT and ALS #3 will have the least. Figure 2 shows the loading characteristics of these three distributions.

Table 2. Characteristics of ALS and N to cause similar ESALs

ALS No.	Load Spectra Characteristics							ESALs	Normalized ADTT	ADTT
	μ_1	μ_2	σ_1	σ_2	P_1	N	X_s			
1	60	120	14	20.0	0.30	2,743,626	148	1.E+06	1.0	15,000
2	70	160	15	25.0	0.50	1,225,022	148	1.E+06	2.2	6,818
3	80	170	20	25.0	0.30	707,262	148	1.E+06	3.9	3,846

**Figure 1. Axle load spectra having similar ESALs****Figure 2. Axle load spectra having dissimilar ESALs**

Once the load spectra are obtained, the next step is to use these ALSs in the M-E PDG to assess their impact on the predicted pavement performance.

Impact of Different Traffic Characterization on Rigid Pavement Performance

In this study, the effects of loading characteristics and traffic levels in terms of repetition on pavement performance were evaluated using version 1.0 of the M-E PDG software. Two JPCP pavement cross-sections (15 ft. doweled joints) were assumed with 9-inch (thin) and 11-inch (thick) slab thickness over an 8-inch thick crushed gravel base on A-6 subgrade. It should be noted that all structural, environmental and materials related inputs were fixed in this analysis and only the effects of traffic loadings (axle load spectra) and traffic levels (repetitions) on JPCP performance were studied. The six tandem axle load distributions were used to investigate pavement performance after 30 years of service life. The impact of the two traffic characterizations were evaluated for cracking, faulting, and roughness (IRI), as predicted by M-E PDG.

ALS with equivalent ESALs. Three axle load spectra (see Table 1) having similar ESALs were used in the M-E PDG, Figures 3 and 4 show the performance predictions for thin and thick pavements, respectively. It can be seen from these figures that all distress types are somewhat similar with no practical difference between all load distributions except cracking. The cracking model in M-E PDG includes both top-down and bottom-up cracking. Only one type of cracking (top-down or bottom-up) is

assumed to occur at one time. Also, the load combination for top-down cracking assumes a steering axle and a tandem axle. The steering axle is assumed to have a fixed load of 12-kip while the tandem axle has a load spectra distribution. Therefore, to further investigate the accumulated damage only bottom-up cracking information was extracted from M-E PDG output and the % slabs cracked were calculated separately. It was found that bottom-up cracking is different for three equivalent load distributions considered. These results suggest that load spectra may have the unique effect on the cracking performance although they have similar ESALs. However, the difference in cracking between equivalent load spectra is reduced over a longer time period. On the other hand, for all practical purposes, faulting and IRI predictions are similar between different load spectra.

ALS with different repetitions. The second hypothesis tested in this study was to match ESAL from different axle load spectra by changing the number of repetitions. Three load spectra are shown in Table 2 with their respective ADTT to achieve the required ESALs. In this analysis, the uniqueness of each load spectra was not considered and ESALs were matched by changing the repetitions. Figures 5 and 6 show the predicted pavement performance for thin and thick cross-sections, respectively. It can be seen that in this case all the distresses (cracking, faulting, and IRI) are different for each load spectra. Again, the accumulated damage due to bottom-up cracking was used to determine only bottom-up cracking. It was found that predicted cracking performance is significantly different between the three load spectra.

Load spectra with a higher number of repetitions showed higher faulting and IRI development over time for both thin and thick pavements. The trends for cracking reveal that the heaviest load spectra with the least number of repetitions caused the maximum cracking for thin pavement while the lightest load spectra with the highest number of repetitions caused more cracking in thick pavement (see Figures 5b and 6b). In the case of bottom-up cracking, more cracking is caused by the heaviest loadings for both thin and thick pavements.

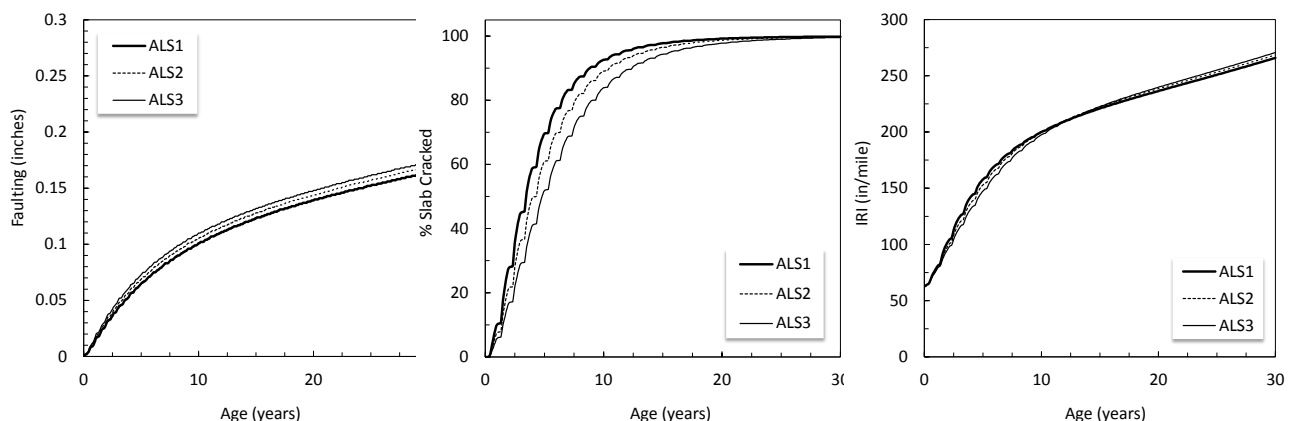
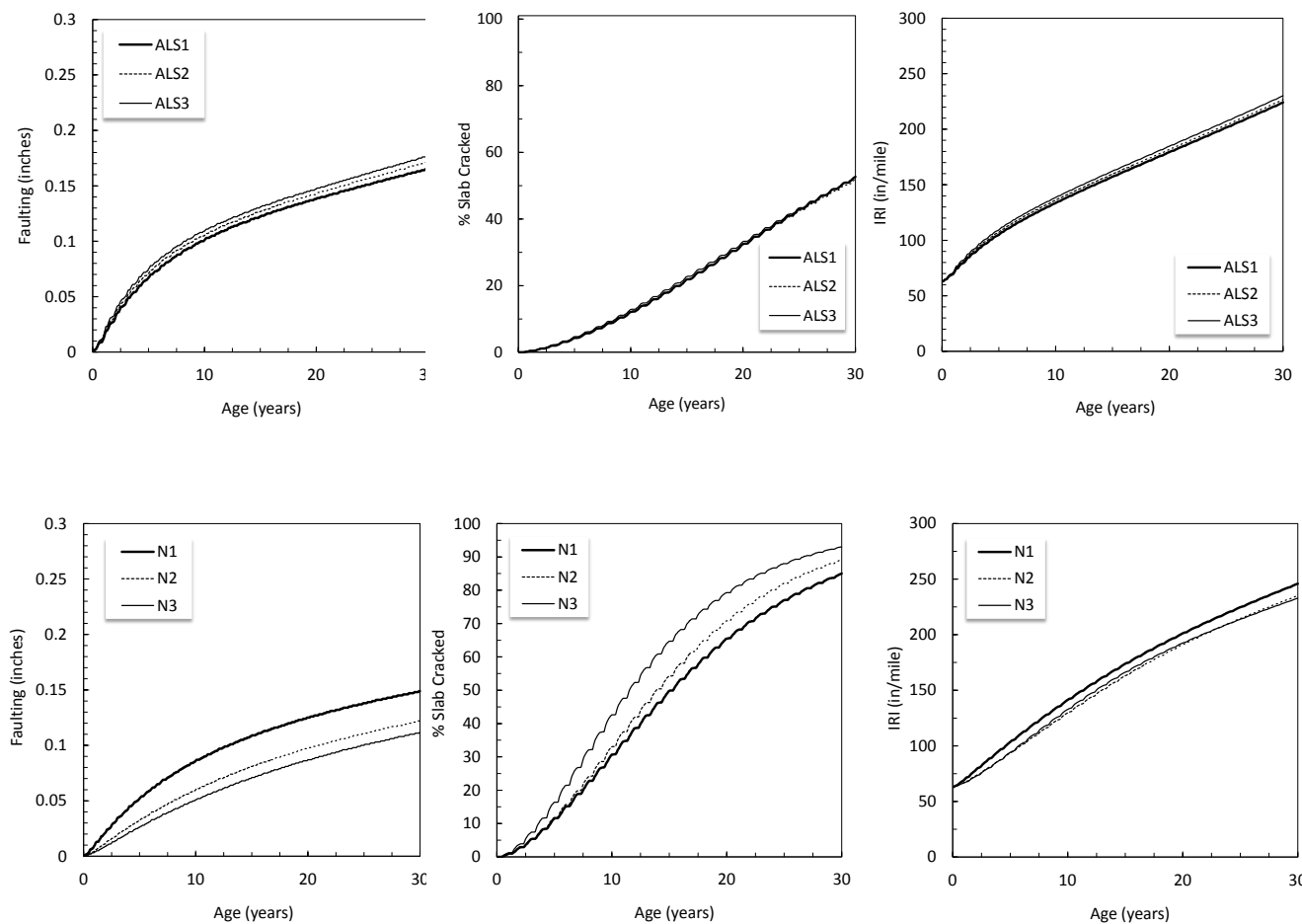
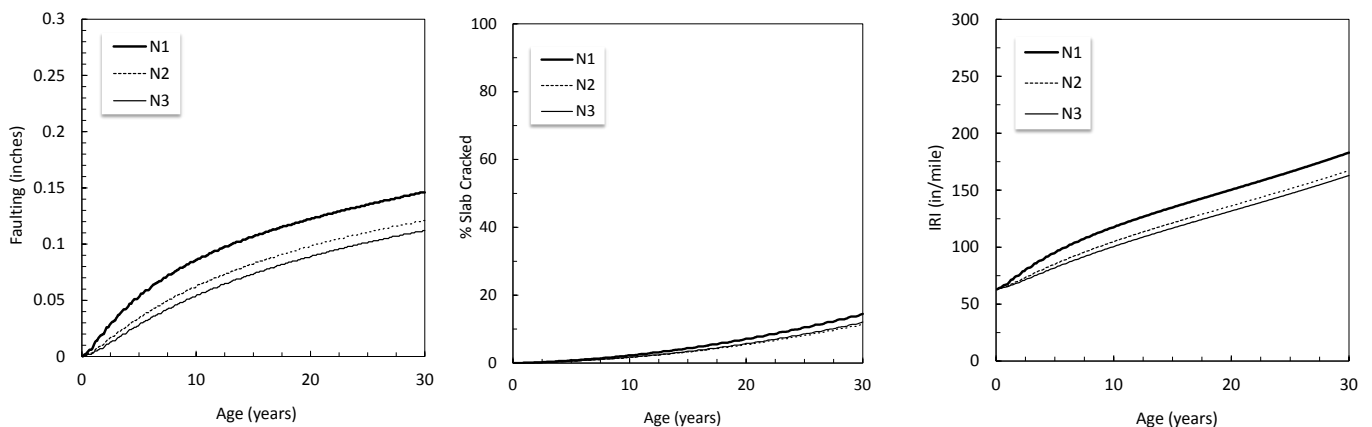


Figure 3. Pavement performance—thin pavement

Figure 4. Pavement performance—thick pavement**Figure 5. Pavement performance—thin pavement****Figure 6. Pavement performance—thick pavement**

Conclusions

For pavement analysis and design, influence of traffic loads and repetitions can be characterized by: (a) ESALs, and (b) axle load spectra. The M-E PDG uses the latter but the analysis in this new design process can be simplified by using equivalent single axle loads (ESALs) for each axle type. Similarly, a concept of equivalent axle load spectra can be used in mechanistic procedures to achieve similar performance

prediction as achieved by using an axle load spectra. The equivalent axle load spectra for each axle configuration can be developed by using site-specific loadings. Alternatively, the number of repetitions (ADTT) can be adjusted to achieve the desired level of ESALs during the design life. The results of this study show that it is important to determine the design ESALs from a site-specific axle load spectra. On the other hand, assuming axle load spectra which are not site-specific and achieving the desired level of ESALs by changing the number of repetitions may not give reliable estimates of expected pavement performance as compared to site-specific axle load spectra.

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