1. Report No. SWUTC/16/600451-00071-1	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle QUANTIFICATION OF INFRASTRUCTURE CONSUMPTION UNDER DIFFERENT AXLE CONFIGURATIONS AND WHEEL LOADS		5. Report Date January 2016
		6. Performing Organization Code
7. Author(s) Ambarish Banerjee, Maria Burton, and Jorge Prozzi		8. Performing Organization Report No.
9. Performing Organization Name and Address Center for Transportation Research University of Texas at Austin 1616 Guadalupe Street, Suite 4.200 Austin, Texas 78701		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. DTRT12-G-UTC06
12. Sponsoring Agency Name and Address Southwest Region University Transportation Center Texas A&M Transportation Institute Texas A&M University System College Station, Texas 77843-3135		13. Type of Report and Period Covered Final Report
		14. Sponsoring Agency Code

15. Supplementary Notes
Project supported by a grant from the U.S. Department of Transportation, University Transportation Centers Program and general revenues from the State of Texas.
Project title: Quantification of Infrastructure Consumption under Different Axle Configurations and Wheel Loads

16. Abstract
Recent developments in the energy sector in Texas, in particular oil, gas and wind energy, have resulted in increased volumes of traffic generated in areas such as the Barnett Shale, Eagle Ford Shale, Permian Basin, the Texas Panhandle, and others. In the case of oil and gas, the development and operation of a well site requires significant number of truck movements (including oversize/overweight loads) that accelerate the deterioration of the surface transportation network of the state faster that what was designed for. This unanticipated and accelerated deterioration of the road network imposes additional burden on already insufficient maintenance and rehabilitation budgets that affect most state highway agencies in the United States. The energy sector contributes immensely to the economic competitiveness of the State of Texas and the Southwest Region of the United States, but, under the present situation, the Texas Department of Transportation (TxDOT) does not have the necessary resources to keep up with reconstruction, rehabilitation or maintenance of the system to keep it safe for the general public. A solution has to be worked out to address this immediate problem.

17. Key Words Oversize, overweight, trucks, OS/OW, Equivalent Damage Factor, EDF, DARWin-ME, Load Equivalency		18. Distribution Statement No restrictions. This document is available to the public through NTIS: National Technical Information Service 5285 Port Royal Road Springfield, Virginia 22161	
19. Security Classif.(of this report) Unclassified	20. Security Classif.(of this page) Unclassified	21. No. of Pages 56	22. Price

Form DOT F 1700.7 (8-72)   Reproduction of completed page authorized

QUANTIFICATION OF INFRASTRUCTURE CONSUMPTION UNDER DIFFERENT AXLE CONFIGURATIONS AND WHEEL LOADS

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ABSTRACT

Recent developments in the energy sector in Texas, in particular oil, gas and wind energy, have resulted in increased volumes of traffic generated in areas such as the Barnett Shale, Eagle Ford Shale, Permian Basin, the Texas Panhandle, and others. In the case of oil and gas, the development and operation of a well site requires significant number of truck movements (including oversize/overweight loads) that accelerate the deterioration of the surface transportation network of the state faster that what was designed for. This unanticipated and accelerated deterioration of the road network imposes additional burden on already insufficient maintenance and rehabilitation budgets that affect most state highway agencies in the United States. The energy sector contributes immensely to the economic competitiveness of the State of Texas and the Southwest Region of the United States, but, under the present situation, the Texas Department of Transportation (TxDOT) does not have the necessary resources to keep up with reconstruction, rehabilitation or maintenance of the system to keep it safe for the general public. A solution has to be worked out to address this immediate problem.

EXECUTIVE SUMMARY

With the sudden growth of the energy industry in Texas, there has been an increased volume of heavy vehicle traffic on Texas' surface transportation network. Because the transportation network was not designed to account for this rise in vehicle traffic, they are experiencing high rates of deterioration; these rates are higher than was expected during design. This unexpected damage imposes additional burden on the maintenance and rehabilitation budgets which are already strained. While the energy sector greatly provides economic resources to Texas, the Texas Department of Transportation (TxDOT) lacks the necessary resources to continuously fund reconstruction habilitation of maintenance of the system to keep it safe for the public. It is urgent to find a solution to address this issue.

This study focuses on oversize/overweight (OS/OW) permitted vehicles. These vehicles are a key reason Texas transportation systems are degrading rapidly. While the damage can greatly be attributed to OS/OW vehicles, it is not known how their damage compares to damage caused by a standard axle load (defined as an 18-kip single axle). After finding a method to compare damage caused OS/OW vehicles in terms of a standard axle load by use of an Equivalent Damage Factor "EDF", EDFs were determined for axle loads and configurations for different pavement and distress combinations. The two pavements used in this study are flexible pavement and rigid pavement. Pavement distresses that were studied for flexible pavement include rutting, fatigue cracking, and roughness. For the second type of pavement, rigid pavement, continuously reinforced concrete (CRC) was used to determine EDF values because it is widely used in Texas. EDFs for CRC were determined for punchouts, and roughness distresses. Also for rigid pavements, axle load factors (ALF) and group equivalency factors (GEF) were determined to calculate EDFs (both ALF and GEF contribute to this value).

The results from this study concluded that for flexible pavements, the test results for rutting and fatigue cracking criteria produce a structural number that is approximately 4. This indicates the fourth-power law is applicable and this method is successful in that is more reliable than currently used procedures. This is partly attributed to the fact that the recently developed DARWin-ME was used in this study. By testing rigid pavement, it was found that of the components that impacts EDF, axle load factor (ALF) and group equivalency factor (GEF), the ALF is not affected by slab thickness. In summary, this study found relationships that enable users to quantify infrastructure damage caused by OS/OW vehicles.

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ACKNOWLEDGEMENTS

CHAPTER 1 - MOTIVATION

Introduction

Recent developments in the energy sector in Texas, in particular oil, gas and wind energy, have resulted in increased volumes of traffic generated in areas such as the Barnett Shale, Eagle Ford Shale, Permian Basin, the Texas Panhandle, and others. In the case of oil and gas, the development and operation of a well site requires significant number of truck movements (including oversize/overweight loads) that accelerate the deterioration of the surface transportation network of the state faster that what was designed for. A similar situation has been observed with the installation of wind mills in West and South Texas, however, in this case, after installation, traffic levels are back to normal. This unanticipated and accelerated deterioration of the road network imposes additional burden on already insufficient maintenance and rehabilitation budgets that affect most state highway agencies in the United States.

There is absolutely no doubt that the energy sector contributes immensely to the economic competitiveness of the State of Texas and the Southwest Region of the United States, but it is also a fact that, under the present situation, it is not sustainable to keep the highway system in a state of good repair because the Texas Department of Transportation (TxDOT) does not have the necessary resources to keep up with reconstruction, rehabilitation or maintenance of the system to keep it safe for the general public. A solution has to be worked out to address this immediate problem.

Oversize/Overweight Loads

The Motor Carrier Division (MCD) of the Texas Department of Transportation (TxDOT) processes over 500,000 oversize/overweight (OS/OW) permits annually. These loads might exceed any of these parameters: 1) the Texas legal axle load limits of 20,000 lbs for single axles or 34,000 lbs. for tandem axles (two axles spaced between 40 and 96 in. apart); 2) the 80,000 lbs total gross vehicle weight (GVW) limit; or 3) the legal vehicle dimensions of 8.5 ft wide, 14 ft high, and 65 ft long. The permitted OS/OW vehicles may be self-propelled (e.g., a mobile crane) or might be specialized truck-trailer configurations not readily comparable to a typical 18-wheeler. These permitted loads may travel a distance as short as 10 miles or may traverse the entire state on state and county roads. Depending on the permit type, the GVW may range from 80,001 lbs. to 254,000 lbs. in the Overweight and Mid Heavy weight class or from 254,300 lbs. to greater than 2,000,000 lbs. in the Super Heavy Load class (*1*).

As OS/OW permitted vehicles typically operate at much heavier loads and with specialized equipment configurations, researchers lack a good understanding of the damage caused by OS/OW loads compared to a standard axle load (defined as an 18-kip single axle).

Load Equivalency
The concept of load equivalency between different axle loads and configurations was first introduced as part of the AASHO Road Test in the 1960s. The term Load Equivalency Factor (LEF) was coined based on the findings of the study. However, following the conclusion of the Road Test program, it was realized that the LEF represents a composite number that can be degenerated into partial factors to account for individual aspects including axle loads, configurations, tire pressure, loading rate, and temperature among others. Some of these factors, like tire pressure, was not included as part of the AASHO Road Tests or in the determination of LEFs (*4, 5*). This led to generalization of the LEF concept to incorporate multiple failure criteria based on mechanistic analysis of pavement structures under dynamic traffic loads and led to coinage of the term "Equivalent Damage Factor (EDF)" (*6*). To date, three partial factors have been developed to account for differences in axle loads, configuration, and tire pressure. Prozzi et al. (*7, 8*) suggested the following relationship for determination of EDF_L for a particular axle load, configuration, and tire pressure:

$$EDF = GEF \times ALF \times CSF \tag{1.1}$$

Where,
GEF : Group Equivalency Factor,
ALF : Axle Load Factor, and
CSF : Contact Stress Factor.

Group Equivalency Factor (GEF) is defined as the ratio between the lives of the pavement under a single axle to the life of the pavement under a group of axles, e.g. tandem, tridem, or quads. The load of the individual axles of the group should be the same as the load of the single axle. This factor only takes into account the number of axles and the inter-axle spacing, and expresses the number of single axles that would cause the same damage to the pavement as the group of axles of the same load. Per definition, the GEF of a single axle is one.

Axle Load Factor (ALF) is defined as the ratio between the life of the pavement under a single axle of 18kip and the life of the pavement under a single axle of different load. The name ALF is proposed because this factor only takes into account the effect of axle load. It is similar to the original LEF but the name was changed to differentiate because of the multi-criteria approach and the mechanistic-empirical formulation.

Contact Stress Factor (CSF) is the ratio between the lives of the pavement under a dual-wheel single axle with a tire pressure of 120 psi and that under a dual-wheel single axle with a different tire pressure.

In summary, the framework proposed by Prozzi et al. (*7, 8*) aims to establish EDF for different axle loads and configurations through quantification of each of these partial factors. However, it is important to note that this study adopts a reverse approach wherein the EDF is determined first followed by subsequent decomposition into ALF and GEF.

Other studies have also used a similar approach where the authors have evaluated the effects of tire pressure, axle load, and axle configuration at highway speed on instrumented test sections. One such study reports that the American Association of State Highway and Transportation Officials (AASHTO) LEF's for single axles with wide-base tires are higher than those found in their study. In the case of tandem axles, the authors reported that the AASHTO LEFs were approximately equal to those reported in the study (*9*).

Figure 1 summarizes the load-equivalency concepts of ALF, GEF, CSF, and EDF with examples illustrated.
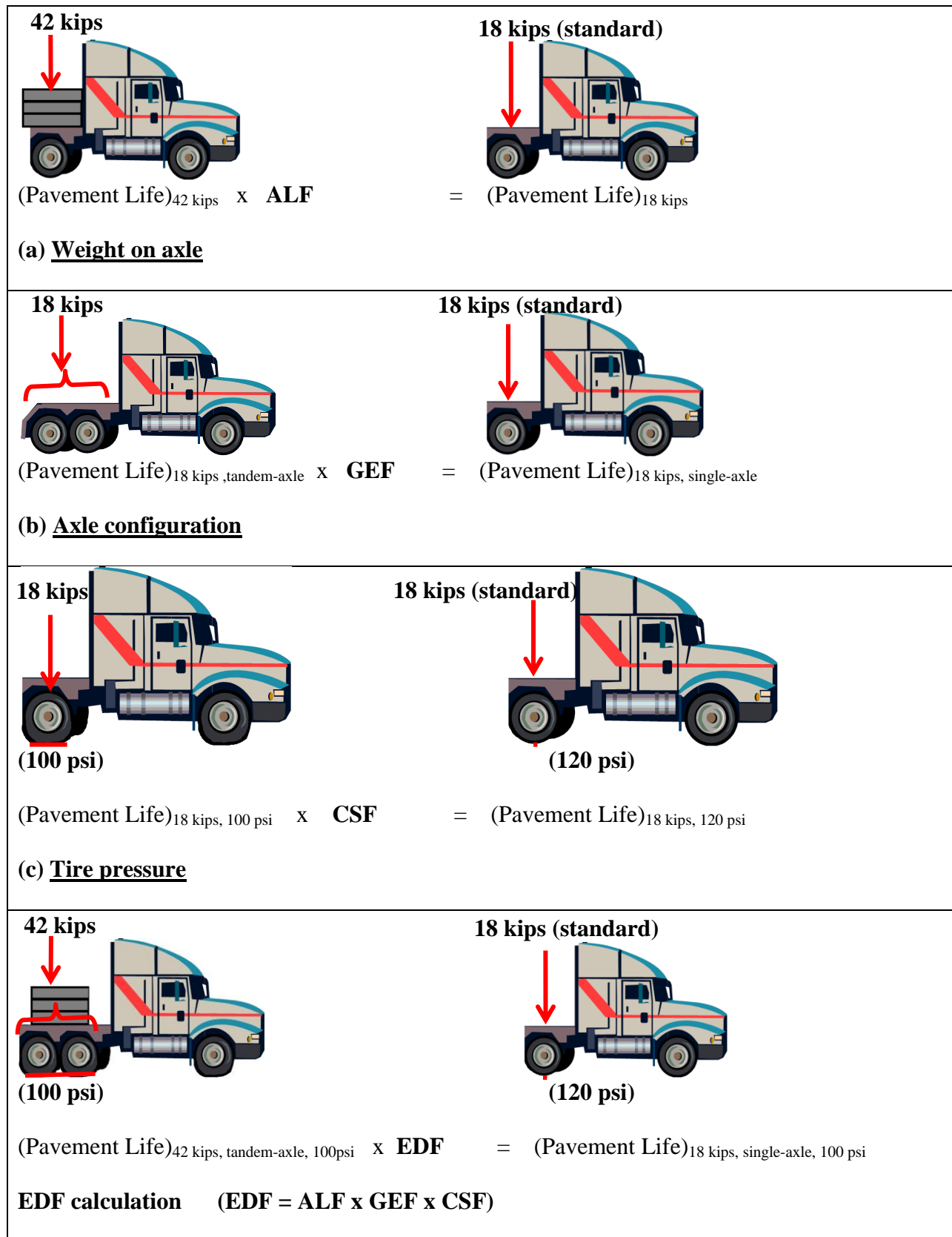
42 kips

18 kips (standard)

$(\text{Pavement Life})_{42\text{ kips}}$ x **ALF** = $(\text{Pavement Life})_{18\text{ kips}}$

(a) Weight on axle

18 kips

18 kips (standard)

$(\text{Pavement Life})_{18\text{ kips, tandem-axle}}$ x **GEF** = $(\text{Pavement Life})_{18\text{ kips, single-axle}}$

(b) Axle configuration

18 kips

18 kips (standard)

(100 psi)

(120 psi)

$(\text{Pavement Life})_{18\text{ kips, 100 psi}}$ x **CSF** = $(\text{Pavement Life})_{18\text{ kips, 120 psi}}$

(c) Tire pressure

42 kips

18 kips (standard)

(100 psi)

(120 psi)

$(\text{Pavement Life})_{42\text{ kips, tandem-axle, 100psi}}$ x **EDF** = $(\text{Pavement Life})_{18\text{ kips, single-axle, 100 psi}}$

EDF calculation   **(EDF = ALF x GEF x CSF)**

Figure 1: Examples summarizing EDF calculation using (a) ALF, (b) GEF, & (c) CSF

MEPDG/DARWin-ME

The DARWin-ME software, which can simulate pavement distresses, uses the same mechanistic-empirical concepts as its predecessor: the Mechanistic-Empirical Pavement Design Guide (MEPDG). The pavement performance prediction models, as well as the required inputs, are the same in either of the programs. However, DARWin-ME represents a significant improvement over the MEPDG in the sense that the computation time is nearly one-tenth of what it used to be for a similar pavement structure. Furthermore, the software was designed to take advantage of and utilize multiple CPUs for running analyses (*15*).

Objectives of Study

Currently state agencies and affected counties are only implementing a reactive approach, that is, highways are repaired only after they have been damaged to an unacceptable level of service. It is well established that this approach is not optimal and it is probably the most expensive and inefficient approach. By having data on wells' site licenses, the state and county authorities will be able to apply sound pavement management principles and make use of preventive maintenance measures.

In this study, a mechanistically-based methodology was developed and utilized to estimate the damage caused to the surface transportation infrastructure. As part of this task, the researchers used the recently released DARWin-ME design guide and software. DARWin-ME is a product approved by the American Association of State Highway and Transportation Officials (AASHTO) and it is endorsed and supported by the Federal Highway Administration (FHWA). Thus, this system is deemed ideal for the current study because it can be applied to the federally-funded and the state-maintained highways systems, i.e. IH, US, SH and FM systems.

The outcome of the mechanistically-based analysis produces the rational for establishing the proportion of damage that can be attributed to the traffic generated by the oil and gas industries and will be used to establish costs for addressing reconstruction, rehabilitation and maintenance needs.

With the elements developed from the previous steps, a management system can be proposed that will enable the State Highway Agencies in the region and local authorities to make better utilization of their limited resources.

Equivalent Damage Simulations

In the context of this study, a certain pavement structure that reaches the pre-set failure criteria under a given axle load and configuration is defined as having equivalent performance (or equivalent damage) to a different loading condition that also results in the same distress level. This study establishes a relationship between the equivalent damage of various axle loads and axle configurations on various pavement types with different structural capacities operating under different environmental conditions. These load equivalencies can facilitate the

determination of the marginal consumption of service life of highway infrastructure which will provide the basis for permit cost calculation.

The study focuses on investigation of the equivalent damage due to individual axles since "pavements feel axle loads not gross vehicle loads." The proposed methodology is beneficial in the sense that it allows the adoption of a modular approach towards calculation of load equivalency for any given truck configuration: the total vehicle damage due to a combination of different axles is equivalent to the linear combination of the damage due to each of the individual axles (*2, 3*).

Two different pavement types were simulated with DARWin-ME in this study and their respective EDF's calculated: flexible pavements (Chapter 2) and rigid pavements (Chapter 3).

CHAPTER 2 - FLEXIBLE PAVEMENT EDF

This section of the study focuses on developing a methodology to establish equivalencies between OS/OW vehicles based on the concept of equivalent damage (or equivalent pavement performance) to the flexible pavement structure using state-of-practice mechanistic-empirical design procedures. In the proposed methodology, each pavement section is evaluated using three different distress criteria: rutting, load-associated fatigue cracking, and roughness.

Methodology
Calculation of EDF

This chapter aims at establishing EDF for different axle loads and configurations for flexible pavement sections using Mechanistic-Empirical design procedures. The fundamental principle behind the proposed methodology involves assumption of equivalencies between different axle loads and configurations that result in the same level of visual distress. However, in establishing such equivalencies, a standard 18-kip single axle has traditionally been used as the reference.

Recent studies have shown that the EDF for different axle loads and configurations are also a function of the bearing capacity of the pavement structure (*10, 11*). Thus, it was essential to evaluate the EDF for different axles over a wide spectrum of pavement structures ranging from thin bituminous surface courses to full-depth asphalt pavements.

The load equivalencies are established based on the notion of time to reach a certain failure criteria. The terminal distress values used as part of this study were decided after consideration of common practices. These are as given below:

- 0.5 inches of rutting at the end of the design life (20 years)
- 10% of the cracked area at the end of the design life
- 125 inches/mile of roughness in terms of International Roughness Index (IRI) at the end of the design life

Each pavement was designed to reach the terminal distress values under the given traffic conditions at the end of its design period. Due to inherent differences in the various failure mechanisms, it is not possible to reach the three terminal distress values simultaneously at the end of the design period with the same traffic volume. It becomes necessary to determine the required traffic volume that would result in a terminal distress value equal to the failure criteria mentioned above. Thus, the traffic volumes calculated will depend on the distress mechanism being considered.

In the following step, each of the pavement structures is analyzed over a range of different axle loads and configurations. Axle loads with EDF less than one take longer than 20 years to reach one of the failure criteria while for the same axles but with EDF greater than one this occurs in less than 20 years. The following is the equation used for calculation of the EDF in the study:

$$EDF = \frac{N_{18}}{N_L} \hspace{10cm} (2.1)$$

Where

N_{18}: number of repetitions to failure of a standard 18-kip single axle; and
N_L: number of repetitions to failure of any given axle load "L".

EDF represents the relative pavement life for any given axle load with respect to the expected pavement service life for the same number of repetitions of an 18-kip standard axle. The methodology adopted also benefits from the fact that systematic differences in the distress predictions will mutually cancel out as the transfer functions used for rutting and cracking mechanisms use a power relationship. However, it is difficult to ascertain that the EDF thus evaluated will be unbiased and therefore using locally calibrated transfer functions will improve the efficiency of the EDFs thus proposed. The analysis of the AASHO Road Test results established that heavier vehicles reduced the serviceability in a shorter time than light vehicles. The results from the test indicated that the damage to the pavement structure varies approximately as the fourth power of the axle load (*12*). These results led to the terminology LEF, where an axle load is said to be equivalent (producing equal pavement wear) to a number of applications of a reference (standard) axle load. While EDF and LEF attempt to capture the same parameter, the term EDF is an enhancement of LEF in the sense that is more generic and accommodates different failure criteria. The AASHTO LEF is expressed mathematically as,

$$LEF = \frac{N_{18}}{N_L} = \left(\frac{W_L}{W_{18}}\right)^4 \hspace{7cm} (2.2)$$

Where

W_L and W_{18} are axle loads and N_L and N_{18} are the corresponding number of load applications.

A logarithmic transformation of Equation 2.2 suggests that there is a linear relationship between LEF and the normalized load in a log-log scale, the slope of this linear relationship being equal to four. This implies that a similar relationship exists between the EDF and ratio of the pavement service life under any given axle load to that of the reference standard axle load in log-log scale. It is important to note that the slope of the line represents the exponent of the power law and it is not a unique number.

Previous studies have shown that the slope depends on the bearing capacity of the pavement structure (*10, 11*). In the case of flexible pavements, the structural capacity could be represented by the structural number (SN). The SN is an abstract number that expresses the bearing capacity required for a given combination of soil support (M_R), total traffic expressed in ESALs, terminal serviceability, drainage and environmental conditions (*13*). However, Deacon et al. (1969) suggested that the structural number of a pavement is not sufficient in itself to

accurately describe the load equivalency factors (*11*). In principle, one should be able to establish a relationship between the exponents of the power law with that of the structural number in the case of flexible pavements.

Due to the multi-criteria approach, one should develop three separate EDFs based on each of the distress criteria mentioned above, however, this will not be practical. For this reason, it is important to establish a weighing scheme which can be applied to the individual EDFs to obtain a generalized EDF. The weighing scheme should be devised such that it takes into account fundamental engineering principles. For example, Texas is divided into 5 different geographical regions. Rutting is more critical in warm climatic regions while cracking is the dominant distress mechanism in colder climatic regions. It is necessary to ensure that the weighing scheme assigns different weights to the individual EDF depending on the climatic region. Another key concern happens to be the inherent variability in the EDFs. There has been discussion regarding the relatively high standard error associated with the fatigue cracking model in the Darwin-ME (*14*). The researchers therefore recommend assigning a lower weight to the EDF calculated using the cracking failure criteria as compared to rutting and roughness such that one may have a higher level of confidence in the overall EDF that is calculated.

Mechanistic-Empirical Pavement Analysis
The study uses the DARWin-ME system for pavement analysis and computation of Equivalent Damage Factors (EDF). In mechanistic-empirical pavement analysis, the fundamental pavement responses under repeated traffic loadings are calculated using a multi-layer linear elastic approach. This approach assumes that a flexible pavement is a layered structure and that each of the layers exhibit a linearly elastic response to traffic loads. The method computes the stresses and strains that are induced in the pavement layers due to traffic loadings. These pavement responses are then related to field distresses using empirical relationships.

Experimental Design
Existing literature suggests that the EDF for any given axle load and configuration partially depends on the structural capacity of the highway facility (*10, 11*). It is important to realize that the location of the pavement determines several site features including the climatic profile and type of subgrade support which, in turn, has a bearing on the structural capacity. For these reasons, it is important to design an experiment that encompasses different pavement structures, traffic levels, and climatic regions (see Table 1).

Table 1: Experimental Design for Determination of EDF

Climatic Region	Pavement Structure	Number of sections		
		Low Traffic	Medium Traffic	High Traffic
Dry-Cold	Granular Base	5	2	0
	Asphalt Base	1	0	1
	Treated Base	1	2	2
	Perpetual Pavement	0	0	0
Wet-Cold	Granular Base	0	4	2
	Asphalt Base	1	2	3
	Treated Base	1	1	2
	Perpetual Pavement	0	0	1
Dry-Warm	Granular Base	1	2	3
	Asphalt Base	1	1	1
	Treated Base	0	0	1
	Perpetual Pavement	0	0	4
Wet-Warm	Granular Base	1	2	0
	Asphalt Base	3	3	2
	Treated Base	2	2	4
	Perpetual Pavement	0	0	0
Mixed	Granular Base	2	3	2
	Asphalt Base	2	2	2
	Treated Base	0	2	1
	Perpetual Pavement	0	0	2

It is evident from Table 1 that a full experiment would be impractical as one would typically not design a perpetual pavement for low traffic volumes. Thus, for the purpose of this study, a partial factorial was designed to address the objectives stated earlier. Table 2 summarizes the range of axle load and configurations that were included as part of this research study.

Table 2: Simulated Axle Configurations and Loads

	Axle Configuration			
	Single	Tandem	Tridem	Quad
	8	18	30	30
	10	22	36	36
	12	26	42	42
	14	30	48	48
Axle Loads (in kips)	16	34	54	54
	18	38	60	60
	20	42	66	66
	22	46	72	72
	24	50	78	78

Determination of EDF for Rutting

Equation 2.1 suggests that it is possible to establish a linear relationship between the EDF and the normalized load on a log-log scale. Figure 2 shows the relationship between these two variables, although the slope varies between the different sections included in this study. Please note that Sections 01 and 02 have been used as representative sections to demonstrate the relationship. However, the full experiment includes 82 different sections located in five different climatic regions with three different traffic levels (as shown in Table 1).

The fact that the slope of the line differs from section to section indicates that the EDF for any given axle load and configurations is influenced by the structural capacity of the highway facility. For the case of tandem, tridem and quad axles, the group equivalency factor was introduced for establishing the EDF. As discussed previously, in the case of single axles, the group equivalency factor is one and therefore the EDF and the ALF are synonymous. In the context of this study, the GEF was incorporated in calculating the normalized load. The following generalized expression was used for calculation of the EDF for any given axle load and configuration while using the rutting failure criteria:

$$ln(EDF) = \alpha \times ln\left(\frac{W_L}{\beta \times W_{18}}\right) \tag{2.3}$$

Where

α   :   Axle Load Factor (ALF), and
β   :   Group Equivalency Factor (GEF).

In general, it was noticed that the ALF is fairly consistent for a given pavement structure for each of the different axle groups, especially in the case of tandem, tridem and quad axles (Figure 2). The determination of GEFs was optimized such that it produces the best linear predictor for the EDF with the normalized load as the independent variable in a log-log scale for all pavement sections included in this study. This implies that the GEFs are least-squares estimates between the observed and the estimated EDFs for each of the different axle configurations included in this study. Following are the GEF values that were estimated for determining the EDF using the rutting failure criteria:
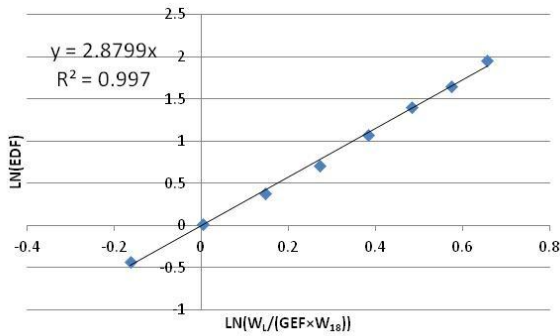
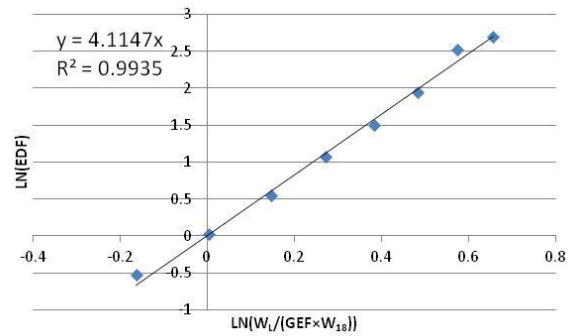- Tandem Axles: 1.44
- Tridem Axles: 1.87
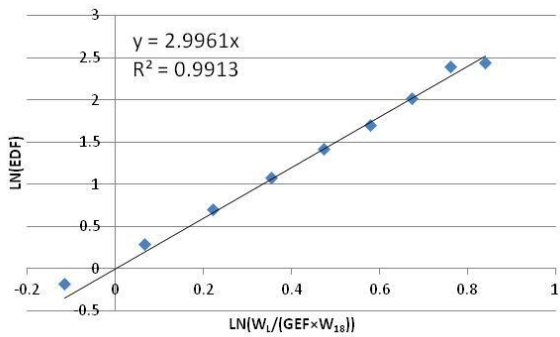- Quad Axles: 2.22
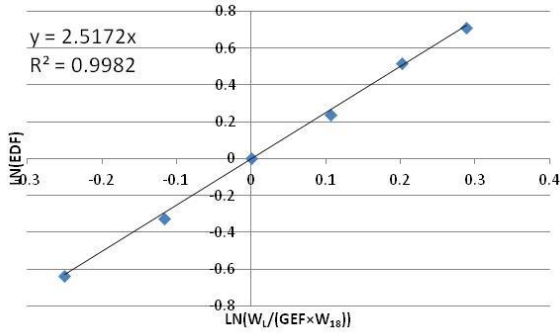
Section 01, single axle
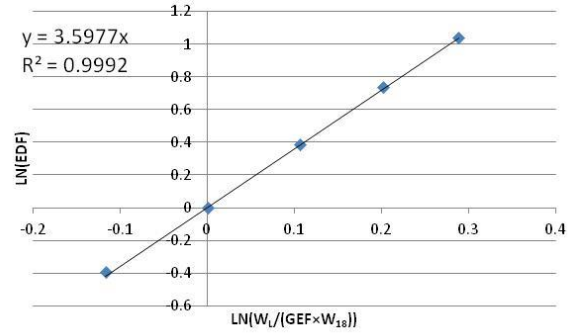
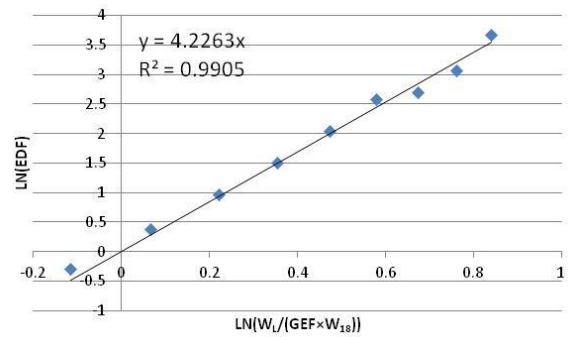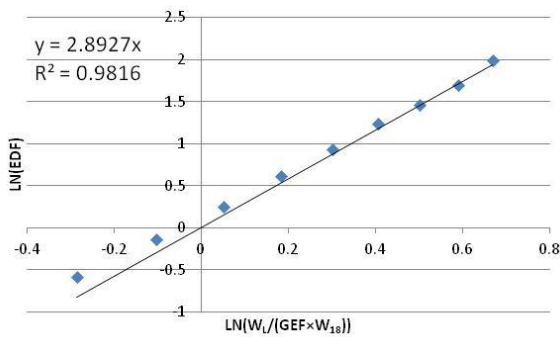Section 02, single axle
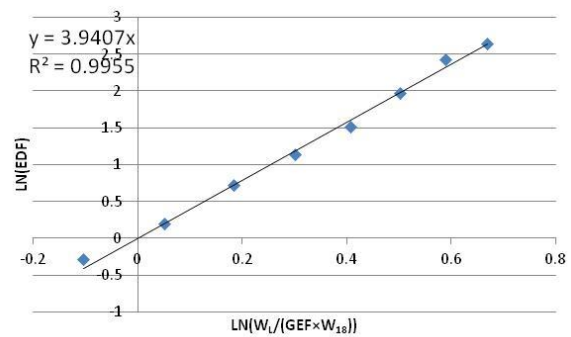

Section 01, tandem axle

Section 02, tandem axle

Section 01, tridem axle

Section 02, tridem axle

Section 01, quad axle

Section 02, quad axle

Figure 2: EDFs based on Rutting Criterion

Several studies have shown that the EDF for different axle loads and configurations are affected by the structural capacity of the highway facility (*5, 7, 8, 10, 11*). In the context of this study, this would imply that the ALF should have a relation with the structural number as the GEF is optimized such that it gives the best linear predictor between the EDF and the normalized load in a log-log scale for all pavement sections included in this study. In theory, one would expect the ALF to decrease for thicker pavements as the structural capacity of a pavement increases exponentially with increasing thickness, making the pavement less sensitive to increases in axle loadings. This relationship is represented in Figure 3.

Single   Tandem

Tridem   Quads
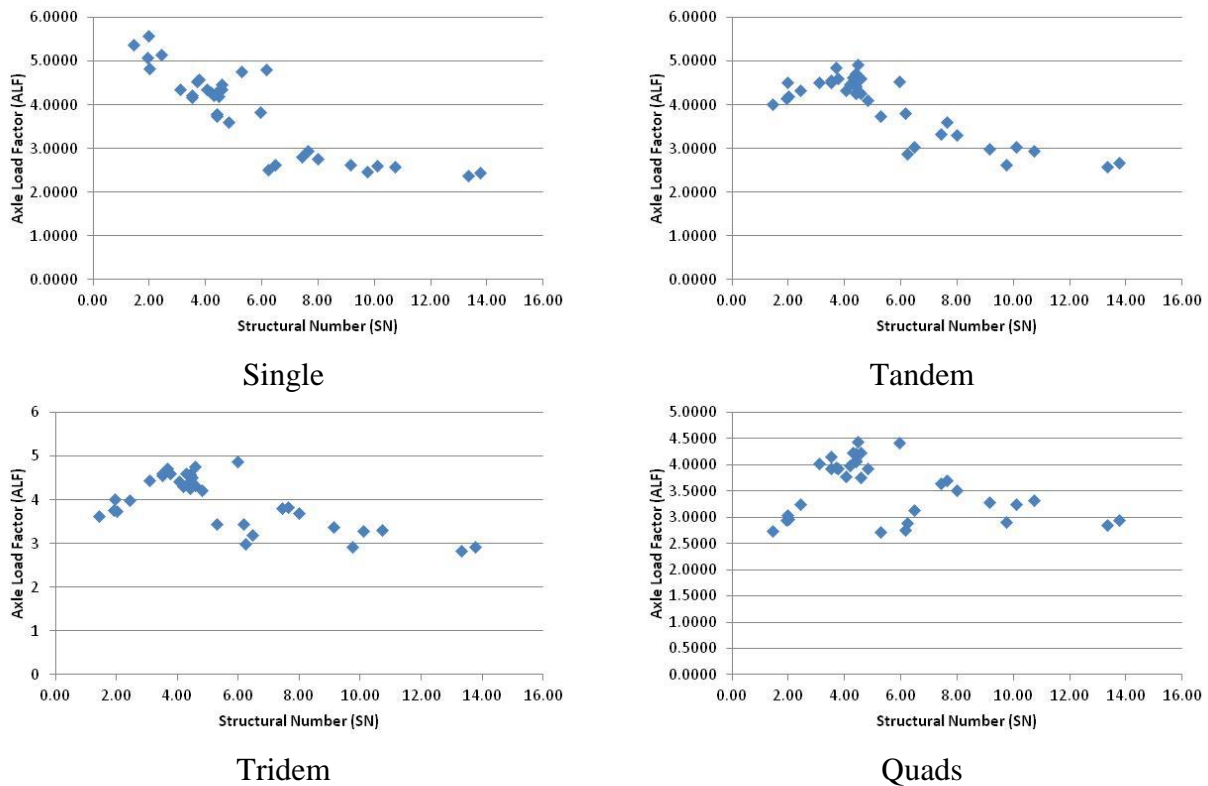
Figure 3: ALF versus SN based on Rutting Criterion

It is clear from Figure 3 that the relationship between the ALF and SN is non-monotonic and also indicates that there is a critical SN beyond which the ALF gradually decreases with increasing or decreasing pavement thickness. However, this pattern is particularly identifiable in the case of tandem, tridem and quad axles and the critical structural number is around 4.0 which, assuming a layer coefficient of 0.44, is equivalent to nine inches of HMA (*16*).

It is also interesting to note that in the case of single axles, the relationship between the ALF and the SN appears to be monotonic and is in agreement with the hypothesis that increasing thickness results in lower maximum strains and therefore values of ALF. This is because there is no confining effect for other axles as in the case on tandem, tridem and quads.

Based on the relationships presented, it was decided to model the ALF for single axles using a power relationship between the ALF and the SN. The model parameters are provided in Table 3. Figure 4 shows the fit of the model with respect to the observed data.
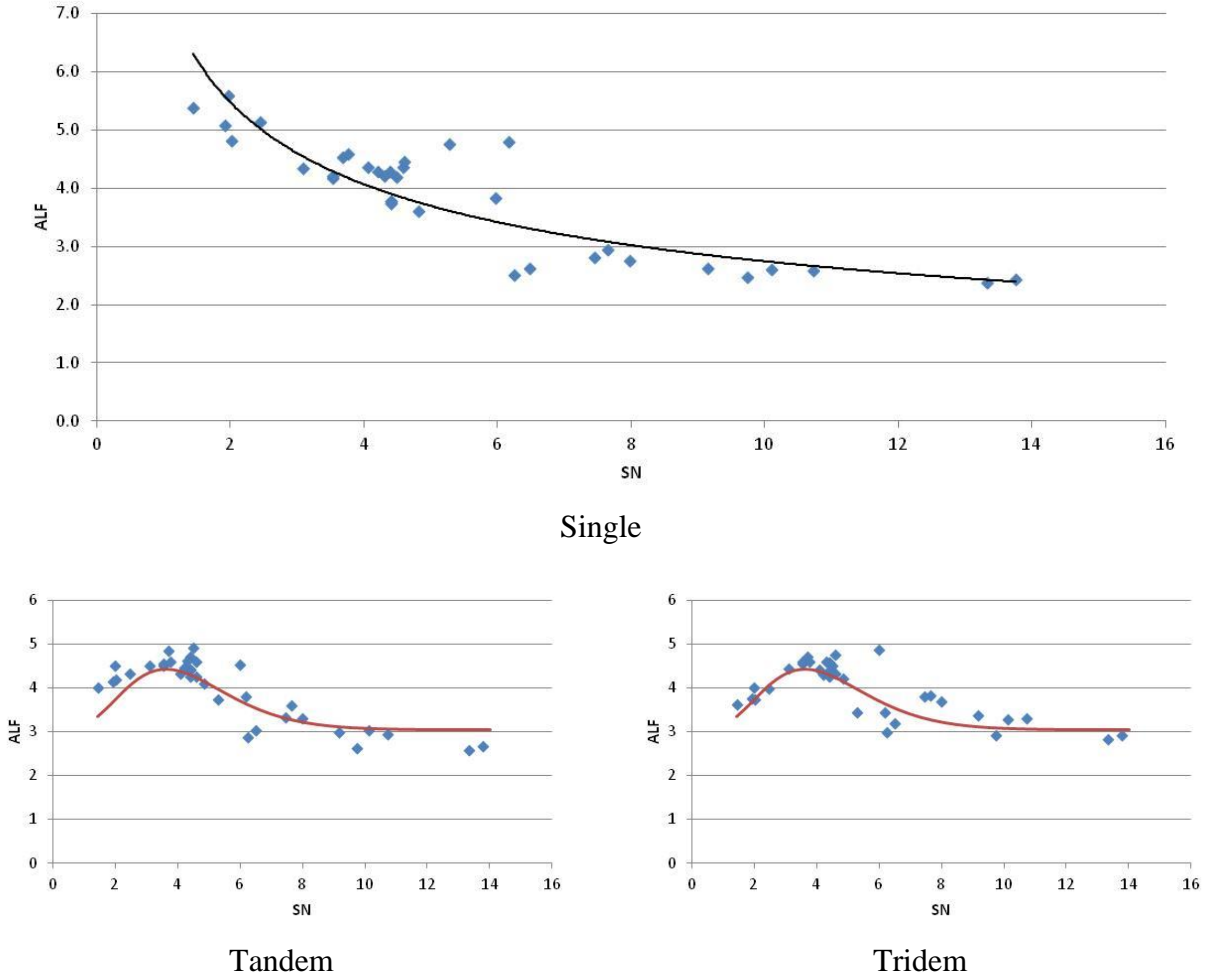

Single

Tandem

Tridem

Figure 4: ALFs based on Rutting Criterion

The following equation shows the final relationship for calculating the EDF for single axles from a rutting standpoint:

$$ln(EDF) = (e^2 \times SN^{-0.43}) \times ln\left(\frac{W_L}{GEF \times W_{18}}\right) \tag{2.4}$$

where e is the base of the natural logarithm and approximately equal to 2.71828…

However, in the case of tandem, tridem and quad axles, data trends suggested that a non-monotonic relationship could provide the best fit. In fact, it was noticed that the ALF starts to bottom out at 2.5 and reaches a peak for structural numbers in the range of 4.0. It was observed that an asymmetric distribution that is positively skewed can be used to model the data. Given these constraints, the following relationship was chosen to construct the model:

$$ALF = \alpha \times SN^{\beta} \times e^{-SN^{\gamma}} + \delta \tag{2.5}$$

Where

$\alpha, \beta, \gamma, \delta$: Regression coefficients.

Table 3: Relationship between ALF and SN

Single Axles			
Standard Error		1.14	
Adjusted R-squared		0.77	
	Coefficient	t-stat	p-value
Intercept	2.00	29.9	0.00
Structural Number	-0.43	-10.7	0.00
Tandem, Tridem, and Quad Axles			
Standard Error		0.42	
	Coefficient	t-stat	p-value
α	0.26	1.90	0.05
β	4.45	5.70	0.00
γ	1.09	14.2	0.00
δ	3.04	27.0	0.00

Figure 4 shows the goodness-of-fit of the model to observed values of ALF. Equation (2.6) is the generalized relationship for computing the EDF for any axle configuration (except single axles) from a rutting standpoint:

$$ln(EDF) = \left(0.26SN^{4.45}e^{-SN^{1.09}} + 3.04\right) \times ln\left(\frac{W_L}{GEF \times W_{18}}\right) \tag{2.6}$$

Where,

SN : Structural Number
EDF : Equivalent Damage Factor
W_L : Axle Load (in kips)
GEF : Group Equivalency Factor
W_{18} : Standard Single Axle carrying 18 kips

Determination of EDF (Fatigue Cracking)

The calculation of EDF from a fatigue cracking perspective was undertaken using the same approach as for rutting. Figure 5 shows the relationship between the normalized loads and the EDF on a log-log scale.

It is evident from Figure 2.4 that the relationship between the normalized load and the EDF can be explained using the same principle as illustrated earlier in Equation 2.2. It is important to note that the rutting and fatigue cracking transfer functions have the same specification (exponential function of strain), which explains why the relationship between these two variables has similar characteristics. However, it was noticed that the ALF values when computed using the fatigue cracking criterion are numerically higher than those calculated using the rutting criteria. In addition it was also noticed that the GEF values were significantly higher:

- Tandem Axles: 1.89
- Tridem Axles: 2.59
- Quad Axles: 3.10

A key observation that was made while calculating the EDF for the different axle loads and configurations using fatigue cracking was that the thin asphalt sections, especially those on top of cement-treated bases (CTB) did not show any visible signs of failure. Fatigue cracking results from tensile stresses exceeding the tensile strength of material due to repeated load cycles. In the case of thin asphalt sections, the governing stress state is primarily compression which explains why these sections failed to reach the terminal fatigue cracking distress criteria.

Several studies in the past have tried to correlate the ALF (the slope of the EDF versus normalized load in log-log scale) to the bearing capacity of the pavement structure. While for the rutting failure mechanism, a noticeable trend was observed for the different axle configurations, the same was missing in the case of the fatigue cracking. Figure 6 illustrates the ALF as obtained for single, tandem, tridem and quad axles using the fatigue cracking.

Due to the absence of a definite trend between the ALF and SN, it was decided to compute an average ALF for each of the axle configurations included in this study. The average of the ALFs for single, tandem, tridem and quad groups are as given below:
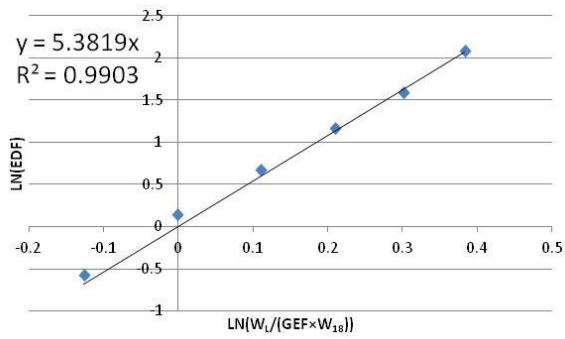
- Single Axles: 5.24
- Tandem Axles: 4.60
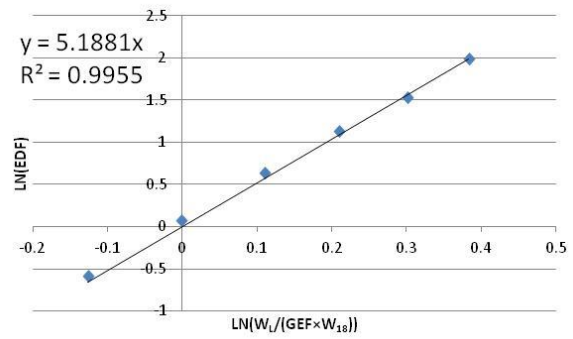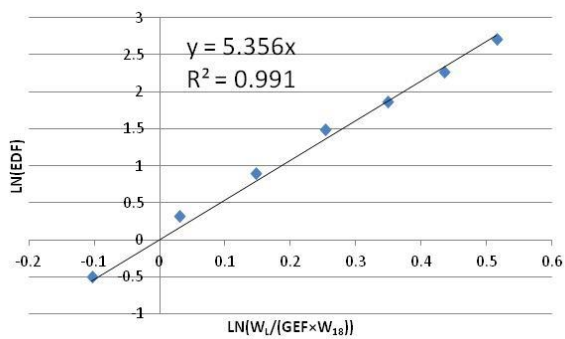- Tridem Axles: 4.42
- Quad Axles: 3.64
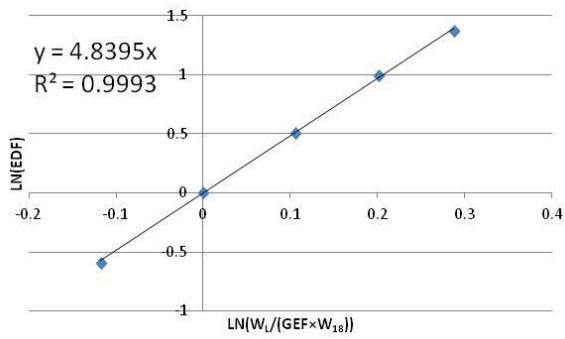
Section 03, Single Axles
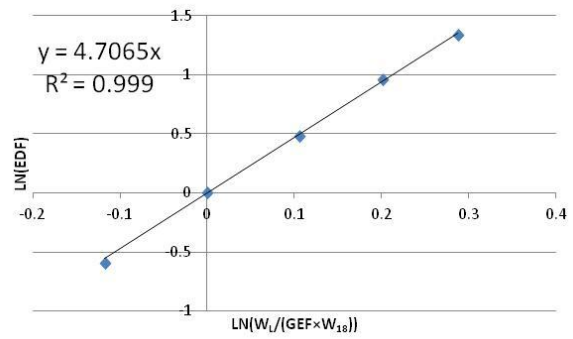
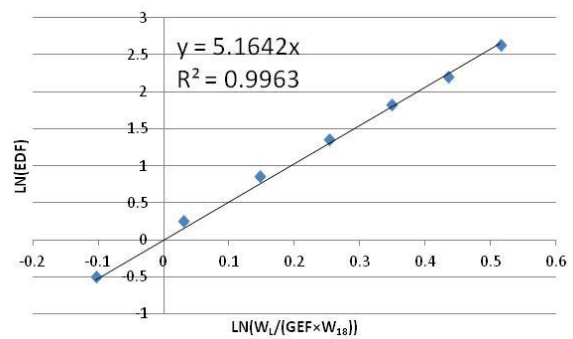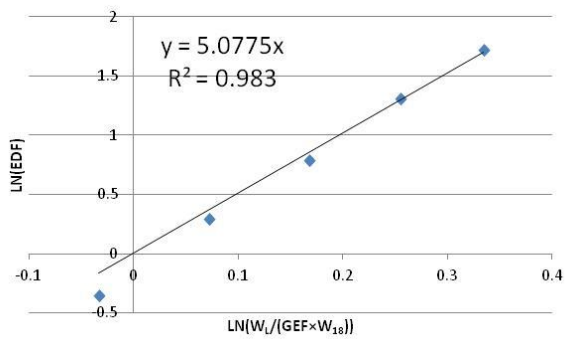Section 04, Single Axles
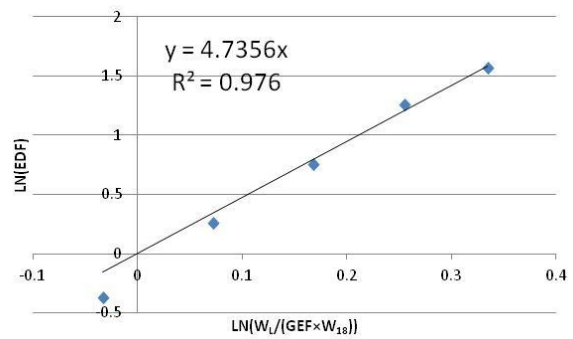
Section 03, Tandem Axles

Section 04, Tandem Axles

Section 03, Tridem Axles

Section 04, Tridem Axles

Section 03, Quad Axles

Section 04, Quad Axles

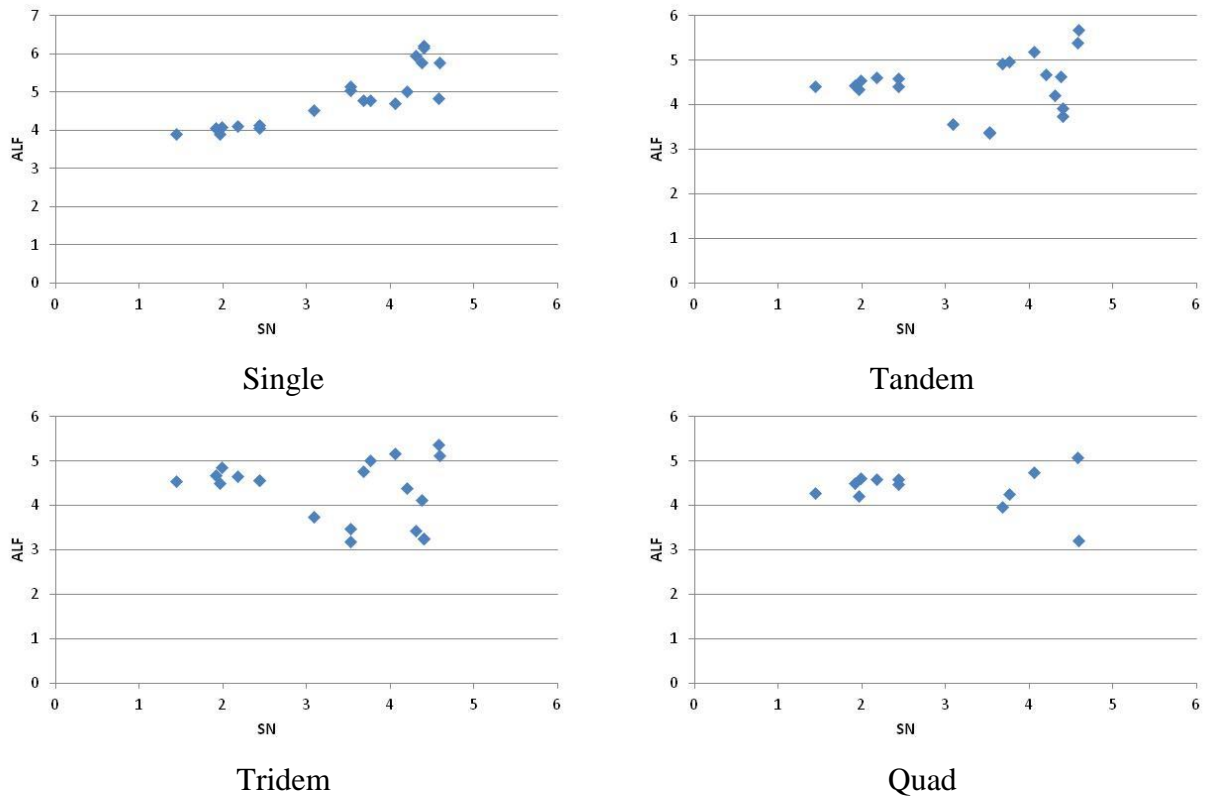**Figure 5**: EDFs based on Fatigue Cracking Criterion

Figure 6: Axle Load Factor versus SN based on the Fatigue Cracking

It was interesting to note that there is a noticeable trend in the mean of the ALFs for the different axle groups. In general, the ALF decreases with increasing number of axles (n) per axle group:

$$ALF = -0.5n + 5.72 \tag{2.7}$$

Equation 2.7 can be used to obtain the final relationship for calculating the EDF for any given axle load and configuration from a fatigue cracking perspective as follows:

$$ln(EDF) = (-0.5n + 5.72) \times ln\left(\frac{W_L}{GEF \times W_{18}}\right) \tag{2.8}$$

Determination of EDF for Roughness

The determination of the EDF from a roughness perspective was approached differently than rutting or fatigue cracking. The initial estimates for the EDF were calculated using Equation 2.1 where the time to failure for a given axle load and configuration were normalized using the time it took for the pavement to fail for standard 18-kip single axles. DARWin-ME uses a transfer function that relates predicted roughness values with other forms of distresses using a linear

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model. Therefore, unlike rutting or fatigue cracking, the EDFs will not follow a power relationship. Figure 7 presents the EDFs for single, tandem, tridem and quad axles for Sections 01 and 02. From a practical standpoint, it is desirable that the EDF for a standard 18-kip axle be equal to one. After evaluating several alternatives, it was realized that the relationship between the normalized load and the EDF can be approximated by an exponential relationship:

$$EDF = e^{ALF \times \left(\frac{W_L}{GEF \times W_{18}} - 1 \right)} \qquad (2.9)$$

It was interesting to note that the GEF values obtained using the roughness failure criteria were significantly different from those obtained using rutting or fatigue cracking:
- Tandem: 1.57
- Tridem: 2.21
- Quad: 2.41

A correlation between ALFs and the bearing capacity of the highway could not be established as there was hardly any evidence suggesting a relationship between these two variables. Following this observation, it was decided to use average ALFs for different axle groups as follows:
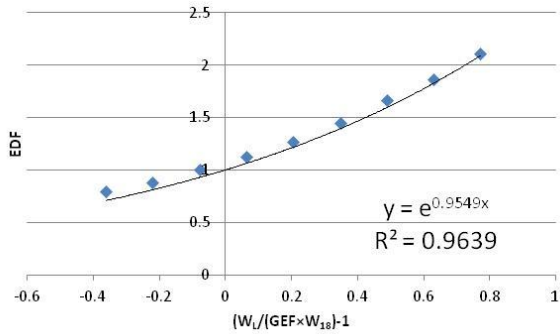- Single: 0.703
- Tandem: 0.962
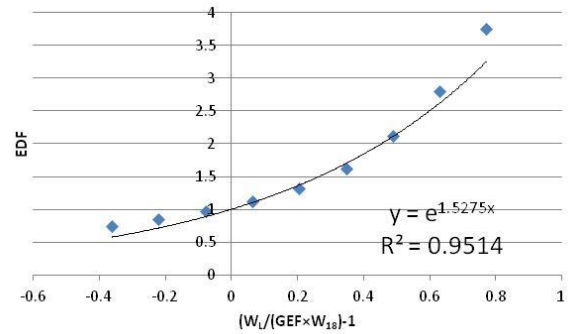- Tridem: 0.943
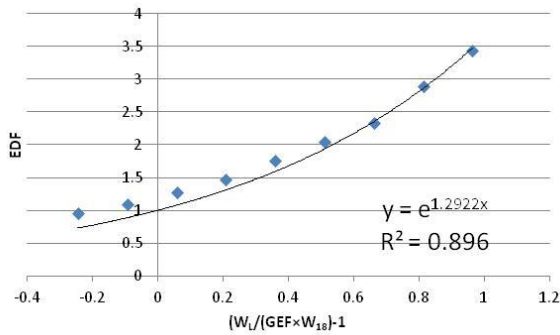- Quad: 0.931
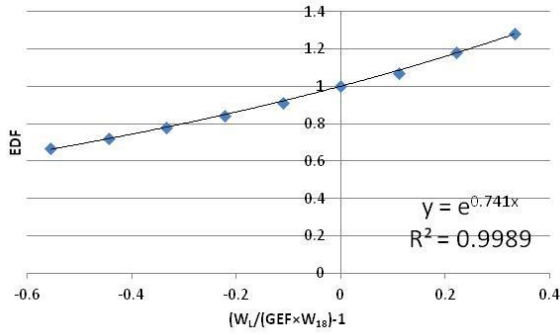
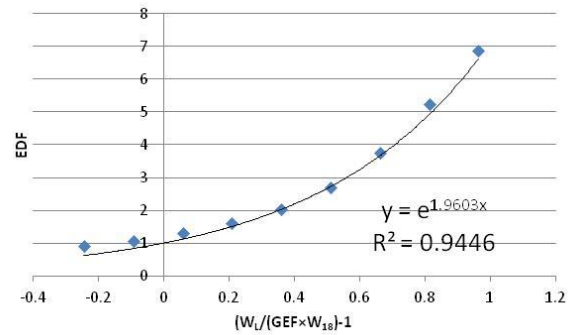Section 01, Single Axles
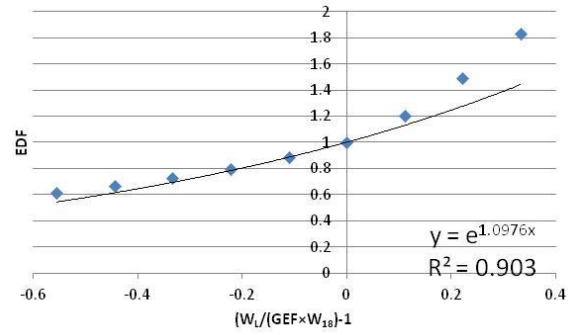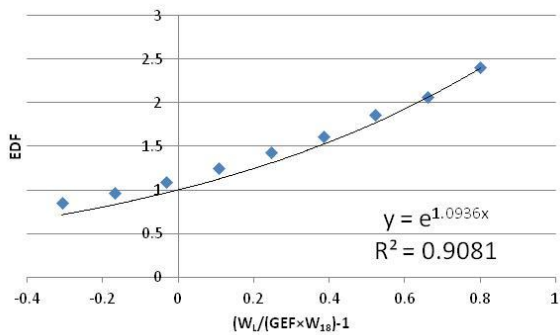
Section 02, Single Axles
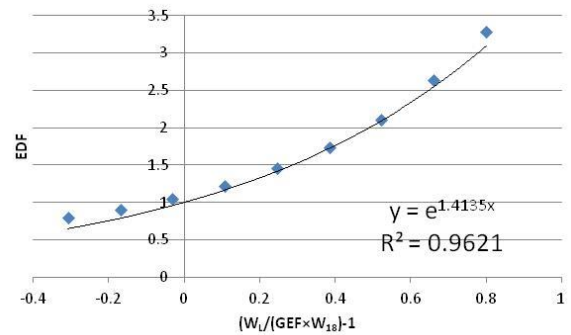
Section 01, Tandem Axles

Section 02, Tandem Axles

Section 01, Tridem Axles

Section 02, Tridem Axles

Section 01, Quad Axles

Section 02, Quad Axles

Figure 7: EDFs based on Roughness Criterion

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Furthermore, it was realized that unlike in the case of fatigue cracking, there was hardly any noticeable trend between the averages of the ALFs for the different axle groups. For this reason and ALF of 0.703 is proposed for single axles and 0.945 for the other axle groups. The final relationship for determination of EDF using the roughness is as given below:

$$EDF = e^{0.703 \times \left(\frac{W_L}{GEF \times W_{18}} - 1\right)} \text{ for single axles} \tag{2.10a}$$

$$EDF = e^{0.945 \times \left(\frac{W_L}{GEF \times W_{18}} - 1\right)} \text{ for tandem, tridem and quads} \tag{2.10b}$$

Application Example

Except for the case of rutting, there was no correlation between EDFs and the structural capacity of the pavement sections. It was also noticed that even though the structural number did not influence the EDFs obtained using the fatigue criterion, a linear relationship between ALF and the number of axles per axle group exists. The EDFs obtained using the roughness criteria did not show a particular correlation.

Following the determination of the individual EDFs, one can apply any weighing scheme that might be most practical and appropriate for the particular region. For this study, equal weights for each of the three distress mechanisms were applied.

A typical 18-wheeler (FHWA's Class 9) loaded to 80,000 lbs GVW with a steering axle carrying 12,000 lbs and two tandem axles each carrying 34,000 lbs would result in EDFs of 7.4, 6.3 and 5.4 on flexible pavement sections with structural numbers of 4, 6 and 10, using the rutting failure criteria. However, the EDF for the same truck when computed using the fatigue cracking or the roughness failure criteria, will be 2.6 and 3.1, respectively, independent of the structural capacity. Therefore, if equal weights are used to compute the EDF for a Class 9 truck traveling on an Interstate highway facility (e.g. SN = 10), the EDF would be 3.7.

Figure 8 shows EDFs computed for two types of 5-axle vehicles under different loading configurations. Although they are both 5-axle vehicles, Class 9 has a steering and two tandem axles while Class 11 has five separate single axles, resulting on different EDFs. This illustrates that the EDF approach presented in this paper could be used by the industry to determine axle configuration and loads which are friendlier to the pavement structure in order to minimize pavement damage and therefore, OS/OW permit fees.
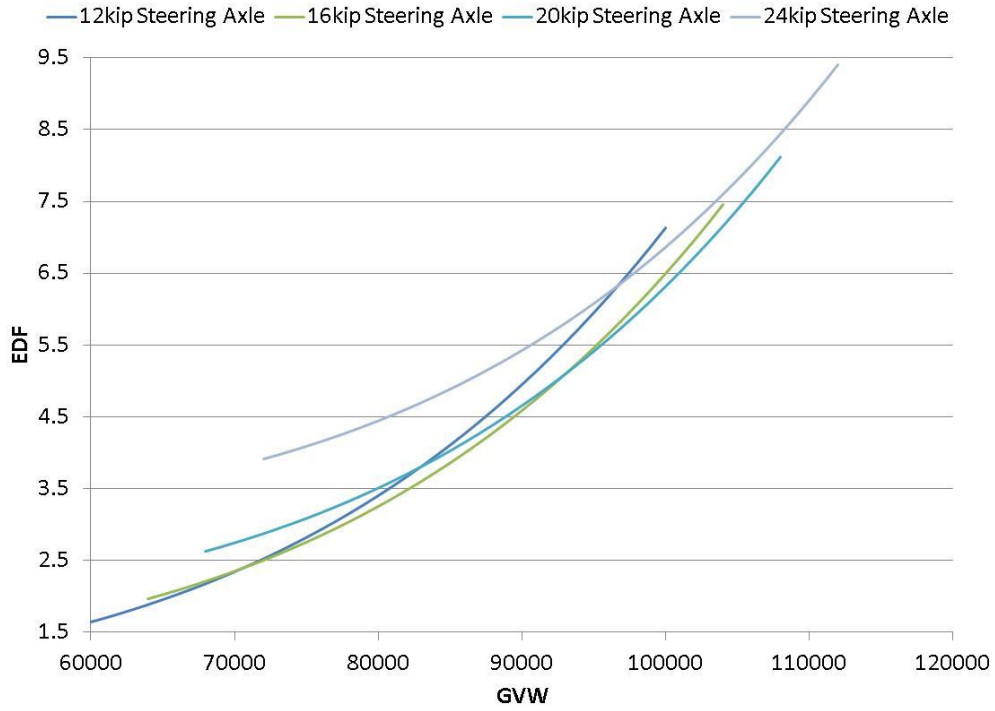
FHWA's Class 9: steering + 2 tandem axles
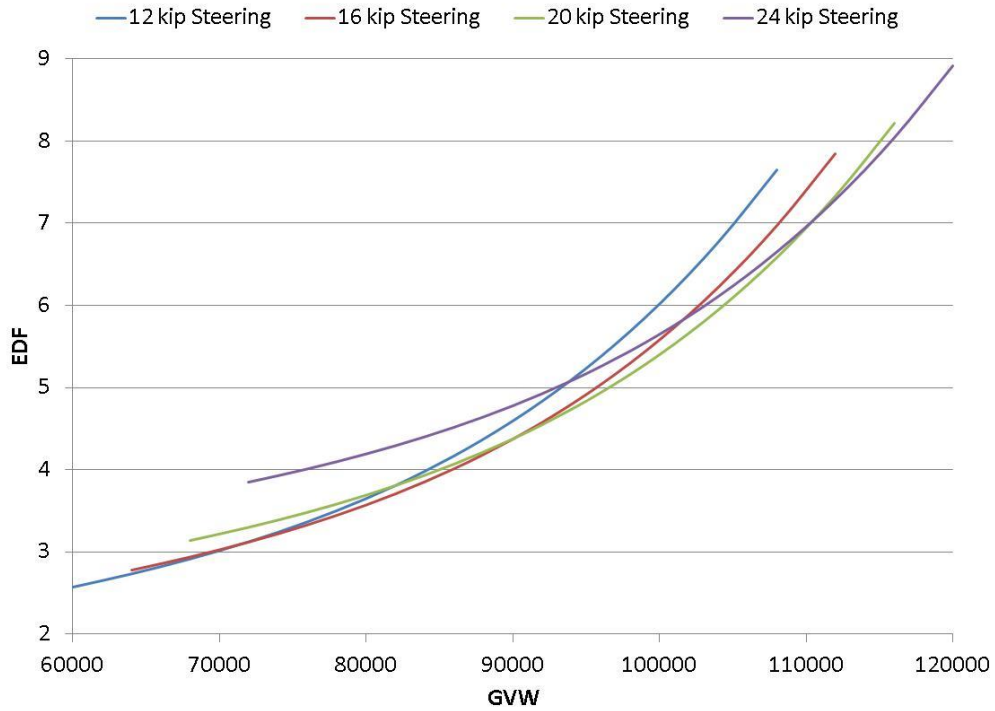
FHWA's Class 11: steering + 4 single axles

FIGURE 2.7:

Figure 8: EDFs calculated for 5-axle vehicles (Class 9 and Class 11)

Conclusions

This chapter presents a methodology for determination of the load equivalencies for different axle and load configuration on flexible pavements to be applied for OS/OW vehicles. The methodology uses a modular architecture that focuses on determination of the EDFs for different axle loads and configurations which can subsequently be added to establish the EDF of any vehicle. It was observed that, except for the case of rutting, the structural capacity of the individual pavement sections had no systematic effect on the EDFs that were calculated. It was interesting to note that the EDFs calculated using the rutting criteria showed that for tandem, tridem, and quad axles, a pavement with a structural number of 4.0 yields the highest ALF. That is, they are the most sensitive to high axle loads while the sensitivity diminishes for both thicker and thinner pavements.

In general, the ALFs computed for flexible pavements using the rutting and fatigue cracking failure criteria are approximately equal to 4 for typical pavement structures (e.g., SN = 4.5). Thus the results presented in this paper are in good agreement with the widely known fourth-power law. However, the methodology proposed herein is wider in application and scope because it uses multiple-failure criteria.

The final section of this chapter shows how one could use the models suggested in this paper in determining load equivalencies for OS/OW permits or for any vehicle in general. It was shown through an example that, for a given GVW, the distribution of loads and axle configuration greatly affect the EDFs. The methodology described in this paper could be used to optimize the distribution of the payload and the axle configuration to minimize infrastructure damage and to reduce potential OS/OW permit fees.

CHAPTER 3 – RIGID PAVEMENT EDF

This section of the study focuses on developing a methodology to establish equivalencies between OS/OW vehicles based on the concept of equivalent damage (or equivalent pavement performance) to the rigid pavement structure using state-of-practice mechanistic-empirical design procedures. In the proposed methodology, each pavement section is evaluated using two different distress criteria: punchouts and roughness.

Methodology
Calculation of EDF
This chapter aims to establish EDFs for various axle loads and configurations for rigid pavement sections using mechanistic-empirical design procedures. The fundamental principle behind the proposed methodology assumes equivalencies between different axle loads and configurations that result in the same level of visual distress. However, in establishing such equivalences, a standard 18-kip single axle has traditionally been used as the reference.

Recent studies have shown that the EDFs for different axle loads and configurations are also a function of the bearing capacity of the pavement structure (*10*). Thus, it was essential to evaluate the EDF for different axles over a wide spectrum of pavement sections with different slab thicknesses.

In Texas, the most common type of rigid pavement that is constructed today is continuously reinforced concrete (CRC) pavements. Therefore, the researchers primarily focused on CRC pavements while determining the EDF for different axle load and configurations on rigid pavements. CRC pavements do not require any contraction joints. Transverse cracks are allowed to form but are held tightly together with continuous reinforcing steel. Research has shown that the maximum allowable design crack width is about 0.5 mm (0.02 inches) to protect against spalling and water penetration (*17*). During the 1970′s and early 1980′s, CRC pavement design thickness was typically about 80 percent of the thickness of JPCP. However, a substantial number of these thinner pavements developed distress sooner than anticipated and as a consequence, the current trend is to make CRC pavement the same thickness as JPCP (*18*). The reinforcing steel is assumed to only handle non-load related stresses and any structural contribution to resisting loads is ignored.

The most prominent visual distress in these pavements is punchouts. Punchouts in CRC pavement are caused by excessive wheel loading applications and insufficient structural capacity of the pavement, such as deficient slab thickness (design issue) or sub-base support (design/construction issue). It manifests as depressed block(s) of concrete, connected by transverse and longitudinal cracks are depressed. Normally, longitudinal steel at the transverse cracks of the punchouts ruptures. Punchouts are by far the most serious distress type in CRC pavement. In addition, roughness remains a major concern in rigid pavements as it directly

relates pavement performance to user costs including traffic delays, maintenance costs and ride quality.

Load equivalencies are established based on the notion of time to reach a certain failure criteria. Therefore in the context of this study, the first step requires establishing the failure criteria. The terminal distress values used as part of this study were decided after consideration of common practices:

- 1 punchout/mile
- 120 inches/mile of roughness in terms of IRI (International Roughness Index) at the end of the design life (initial IRI = 102 inches/mile)

Each pavement was designed to reach the terminal distress values under the given traffic conditions at the end of its design period (30 years in this case). Due to inherent differences in the various failure mechanisms, reaching the two terminal distress values simultaneously at the end of the design period with the same traffic volume is not possible. Thus, determining the required traffic volume that would result in a terminal distress value equal to the failure criteria mentioned above is a necessary step. Therefore, the traffic volumes calculated will depend on the distress mechanism being considered.

Once the design traffic volume is determined, the next step involves the analysis of each pavement structure for a range of axle loads and configurations and the determination of the time to reach each of the aforementioned failure criteria. Axle loads with EDFs of less than 1 will take longer than 30 years to reach the failure criteria, while axles loads with EDFs greater than 1 will need less than 30 years. Following is the equation used for calculation of the EDF in the study:

$$EDF = \frac{N_{18}}{N_L} \tag{3.1}$$

Where

N_{18}: number of repetitions to failure of a standard 18-kip axle; and

N_L: number of repetitions to failure of any given axle load "L".

EDF represents the relative pavement life for any given axle load with respect to the expected pavement service life for the same number of repetitions of an 18-kip standard axle. The analysis of the AASHO Road Test results established that heavier vehicles reduced the serviceability in a shorter time than light vehicles (*12*). These results led to the term LEF, where an axle load is said to be equivalent (producing equal pavement wear) to a number of applications of a reference (standard) axle load. LEF is expressed mathematically as shown in Equation 3.2:

$$LEF = \frac{N_{18}}{N_L} = \left(\frac{W_L}{W_{18}}\right)^{\alpha} \tag{3.2}$$

Where

W_L and W_{18} are axle loads and N_L and N_{18} are the corresponding number of load applications.

A logarithmic transformation of Equation 3.2 suggests a linear relationship between LEF and the normalized load in a log-log scale, the slope of this linear relationship being equal to 'α' in this

case. As noted, the underlying concepts of EDF and LEF are similar, which implies that a similar relationship exists between the EDF and ratio of the pavement service lives under any given axle load to that of the reference standard axle load in log-log scale. Note that the slope of the line represents the exponent of the power law and is not a unique number.

Previous studies have shown that the slope depends on the bearing capacity of the pavement structure (*10*). In the case of rigid pavements, the structural capacity could be represented by the slab thickness. Theoretically, a relationship should exist between the exponents of the power law and those of the slab thicknesses for rigid pavements.

Given the multi-criteria approach, two separate EDFs should be developed based on each of the distress criteria mentioned above, but this is not practical. Therefore, a weighing scheme should be established that can be applied to the individual EDFs to obtain a generalized EDF. The weighing scheme should take into account fundamental engineering principles. Another key concern is the EDFs' inherent variability. For example, the EDF that is calculated using the punchout criteria may have less uncertainty than that obtained using the roughness criteria due to inherent variability associated with the individual transfer functions. In such instances, the researchers recommend that a relatively higher weight should be given to EDFs with lower uncertainty.

Mechanistic-Empirical Pavement Analysis

The study uses the DARWin-ME system for pavement analysis and computation of Equivalent Damage Factors (EDF). In mechanistic-empirical pavement analysis, the fundamental pavement responses under repeated traffic loadings are calculated using a finite element approach. The method computes the stresses and strains induced in the pavement layers due to traffic loadings. These pavement responses are then related to field distresses using existing empirical relationships, also called transfer functions.

Experimental Design

Literature suggests that the EDF for any given axle load and configuration depends to some extent on the structural capacity of the highway facility (*6, 7*). In the case of rigid pavements, the slab thickness can be used as a measure of the pavement's structural capacity. Another important consideration is that the location of the pavement determines several site features, including the climatic profile and type of subgrade support—which, in turn, affects the structural capacity. Therefore, the experiment design must encompass different pavement structures, traffic levels and climatic regions (see Table 4).

Table 4: Experimental design for Determination of EDF

Climatic Region	Traffic Volume		
	Low	Medium	High
Dry-Cold	2	2	2
Wet-Cold	2	2	2
Dry-Warm	1	2	2
Wet-Warm	2	2	2
Mixed	1	2	3

OS/OW loads do not follow the typical legal limits of height, width, length or weight; they can have atypical axle configuration and loads. It is therefore important to simulate a wide range of axle loads with different configurations. Table 5 summarizes the range of axle load and configurations included in this study.

Table 5: Simulated axle loads and configurations

	Axle Configuration			
	Single	Tandem	Tridem	Quad
	8	18	30	30
	10	22	36	36
	12	26	42	42
	14	30	48	48
Axle Loads (in kips)	16	34	54	54
	18	38	60	60
	20	42	66	66
	22	46	72	72
	24	50	78	78

Determination of EDF for Punchouts

Equation 3.2 suggests the possibility of establishing a linear relationship between the EDF and the normalized load on a log-log scale. Figure 9 shows the relationship between these two variables, although the slope varies between the different sections included in this study. Please note that Sections 01 and 02 have been used as representative sections to demonstrate the relationship. However, the full experiment includes 29 different sections located in 5 different climatic regions with 3 different traffic levels (as shown in Table 9).

The fact that the slope of the line differs from section to section indicates that the EDF for any given axle load and configuration is influenced by the structural capacity of the highway facility. For tandem and tridem axles, the GEF was introduced for establishing the EDF. As discussed previously, in the case of single axles, the GEF is 1 and therefore the EDF and the

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ALF are synonymous. In the context of this study, the GEF was incorporated in calculating the normalized load. The following generalized expression was used to calculate the EDF for any given axle load and configuration while using the punchout failure criteria:

$$ln(EDF) = \alpha \times ln\left(\frac{W_L}{\beta \times W_{18}}\right) \qquad (3.3)$$

Where

α	:	ALF, and
β	:	GEF.

In general, the ALF is fairly consistent for a given pavement structure across the various axle groups, especially in the case of tandem and tridem axles (Figure 3.1). The GEF were optimized such that it yields the best linear predictor for the EDF with the normalized load as the independent variable in a log-log scale for all pavement sections included in this study. Following are the GEF values that were estimated for determining the EDF using the punchout failure criteria:
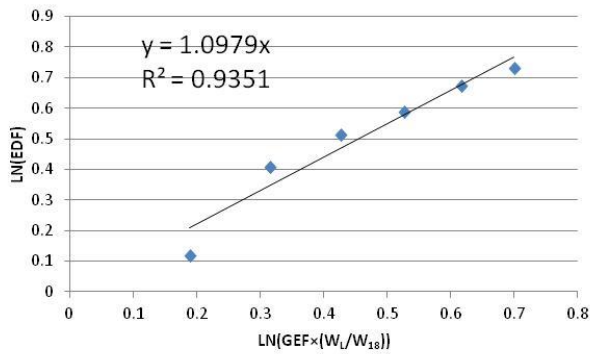
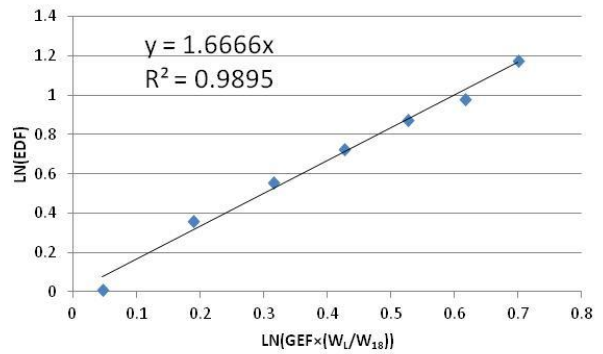- Tandem Axles: 1.38
- Tridem Axles: 2.14
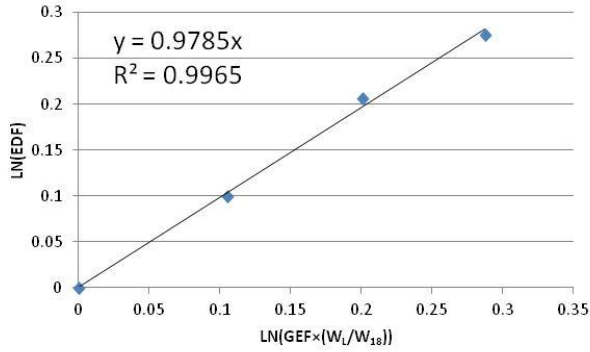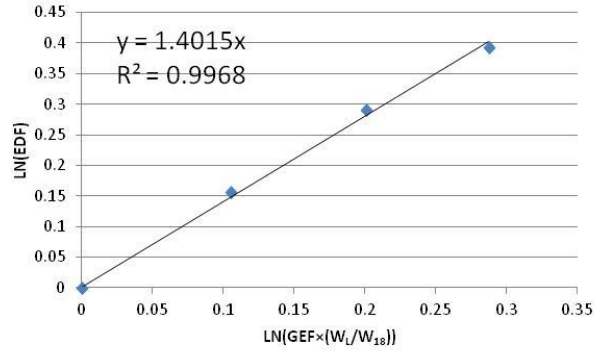
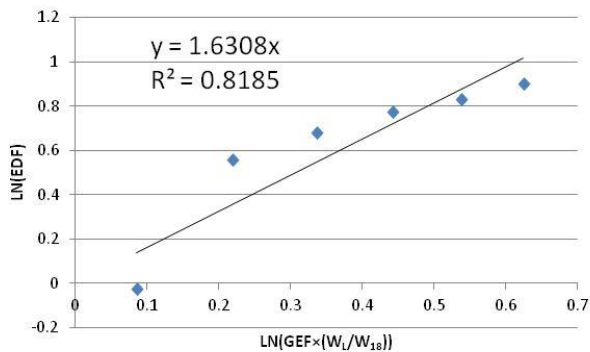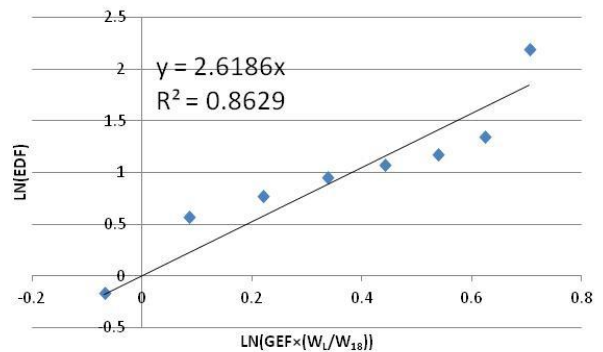**Figure 9:** EDFs based on Punchout Criterion

Figure 9 shows that a linear relationship can explain the relationship between the EDF and the normalized load in the case of single and tandem axles, but not so much for tridem axles. Even then, the fitted line between the log of EDF and the normalized load is a fairly accurate representation between the two variables. However, there is still a systematic trend in the slope of the linear relationship – they increase with increasing number of axles per axle group. In addition, it is also evident that the slope of the line for any given axle group on Section 02 is 1.5 times that computed on Section 01.

In the subsequent step, the study team tried to explore any relationship between the ALF and the structural capacity of the rigid pavement sections. In the case of rigid pavements, the structural capacity of the pavement is best represented by the slab thickness which led the researchers to investigate any relationship that might exist between the ALF and the thickness of the slab. The study team realized that there was hardly any evidence that suggested the possibility of a mutual relationship between the aforementioned parameters (see Figure 10). Furthermore, it was also noticed that the differences in the mean ALF between the axle groups were statistically insignificant. This led the researchers to compute a gross average ALF for the different axle configurations which came out as 3.27.
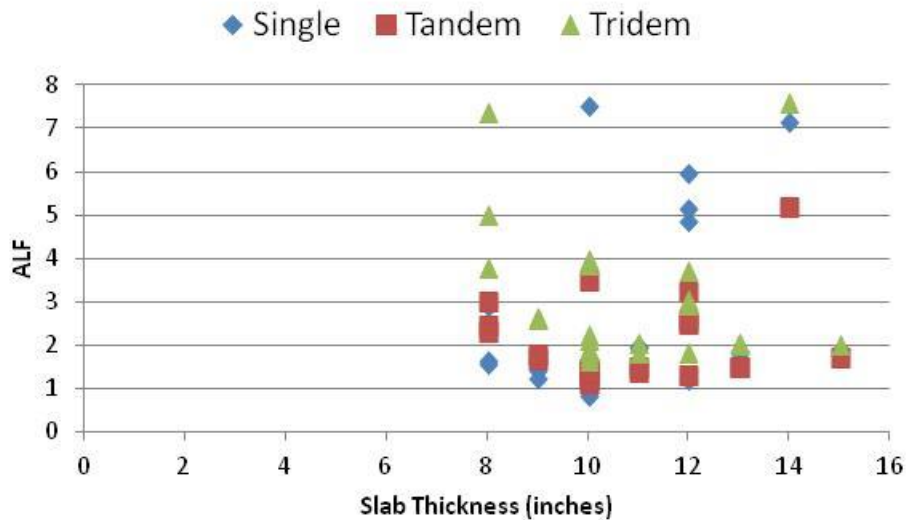

Figure 3.2:
Figure 10: Axle Load Factor V/s Slab Thickness for Rigid Pavement Sections using the Punchout Failure Criteria

Therefore, the final relationship for calculating the EDFs using the punchout failure criteria is:

$$ln(EDF) = (3.27) \times ln\left(\frac{W_L}{GEF \times W_{18}}\right) \tag{3.4}$$

Determination of EDF for Roughness
The determination of the EDF from a roughness perspective was approached differently than the punchout criterion. The initial estimates for the EDF were calculated using Equation 3.1, where the time to failure for a given axle load and configuration were normalized using the time it took for the pavement to fail for standard 18-kip single axles. DARWin-ME uses a transfer function that relates predicted roughness values with punchouts and site-specific features. Therefore, unlike in the case of punchout, the EDFs will not follow a power relationship. Figure 11 presents the EDFs for single, tandem and tridem axles for Sections 01 and 02. From a practical

standpoint, the EDF for a standard 18-kip axle should ideally be equal to 1. After evaluating several alternatives, the researchers determined the relationship between the normalized load and the EDF can be approximated by an exponential relationship:
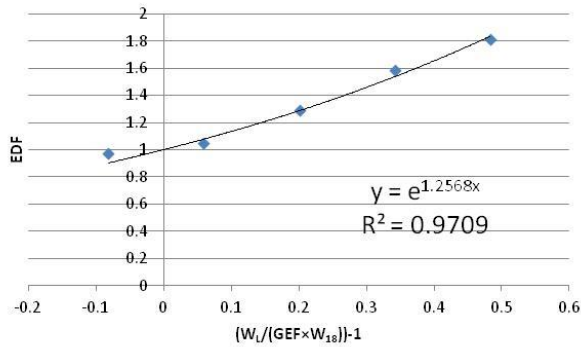
$$EDF = e^{ALF \times \left(\frac{W_L}{GEF \times W_{18}} - 1 \right)}$$
(3.5)
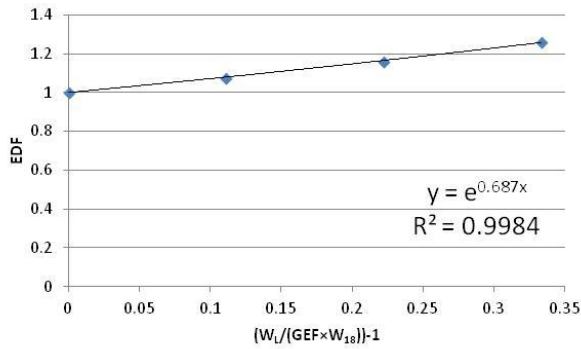
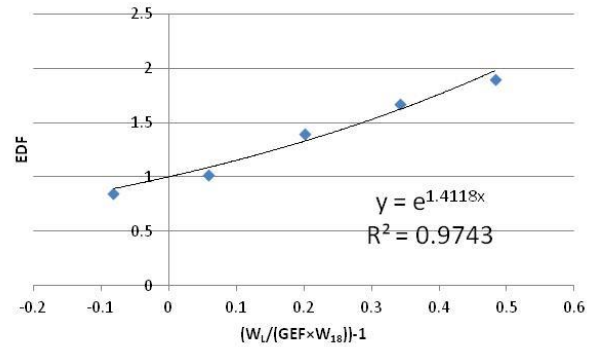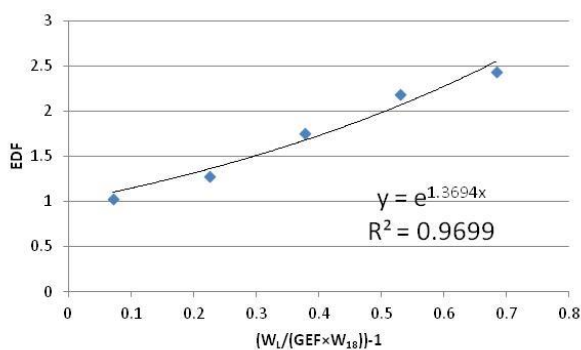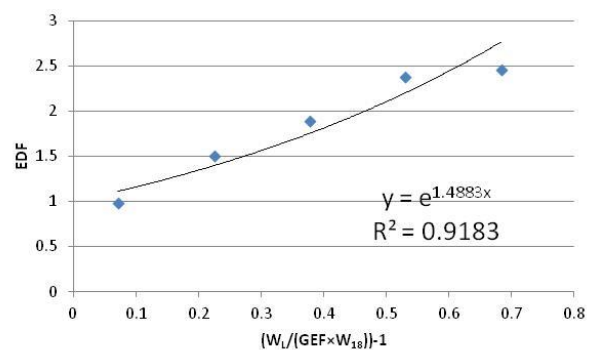

Section 01, Single Axles
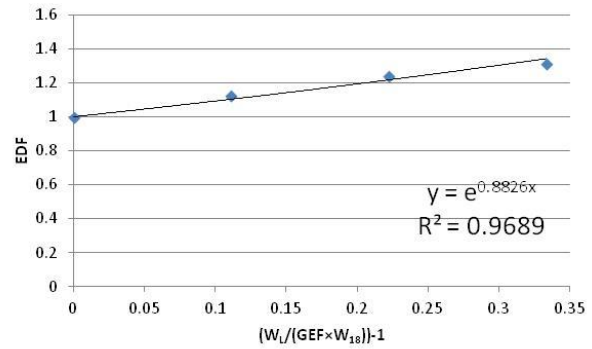
Section 02, Single Axles

Section 01, Tandem Axles

Section 02, Tandem Axles

Section 01, Tridem Axles

Section 02, Tridem Axles

Figure 11: EDFs based on Roughness Criterion

Although Figure 11 suggests that there is a relationship between these two parameters, the exponents thereof vary considerably. As previously stated, the particular observation might be

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attributed to the variability between the different sections in terms of their respective structural capacities, i.e., the slab thicknesses in each of these rigid pavement sections, provided there is strong evidence supporting this statement. However, it was noticed that the observed data did not suggest that the exponents and the slab thicknesses are correlated (see Figure 12). In addition, it was also noticed that the differences in the mean ALF values were no different from each other for the different axle groups. This led the researchers to compute a gross average ALF for any given axle configuration which was equal to 1.46.

The GEFs were computed using the same methodology as adopted earlier in the case of the punchouts and were as given below:

- Tandem Axles: 1.57
- Tridem Axles: 2.18
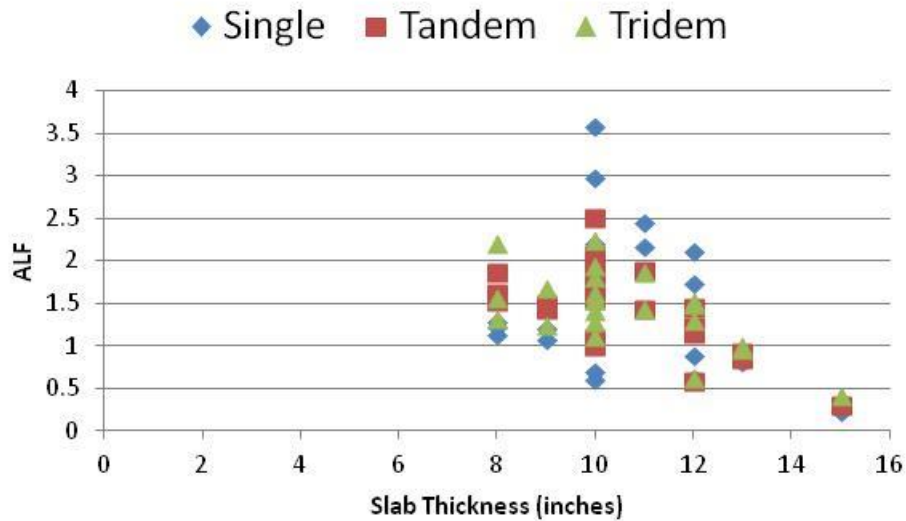
Figure 12: Axle Load Factor V/s Slab Thickness for Rigid Pavement Sections using the Roughness Failure Criteria

The final mathematical relationship for calculating the EDFs using roughness failure criteria is:

$$EDF = e^{1.46\left(\frac{W_L}{GEF \times W_{18}} - 1\right)}$$

(3.6)

Application

Figures 13 and 14 illustrate the EDFs computed for single, tandem, tridem and quad axles using the punchout and roughness failure criteria in the case of rigid pavements. As pointed out earlier, it was noticed that EDFs thus calculated did not appear to be correlated with the slab thicknesses. The figures shown below provide the same modular architecture that has been adopted previously in the case of rigid pavements. If it is assumed that an equal weight is to be assigned

to each of the two failure mechanisms – punchout and roughness, the EDF for a Class 9 truck loaded to 80,000 lbs would respectively be 5.2 and 3.3 using the failure mechanisms stated above. Just as in the case of rigid pavements, additional axles can lower the gross EDF of the truck in the case of rigid pavements too. A similarly loaded Class 10 truck would have EDFs in the range of 3.5 and 2.8 respectively, when evaluated in terms of punchout and roughness measures. Pavement damage is proportional to axle weight, so a higher number of axles could lower the gross EDF for a vehicle with the same payload.
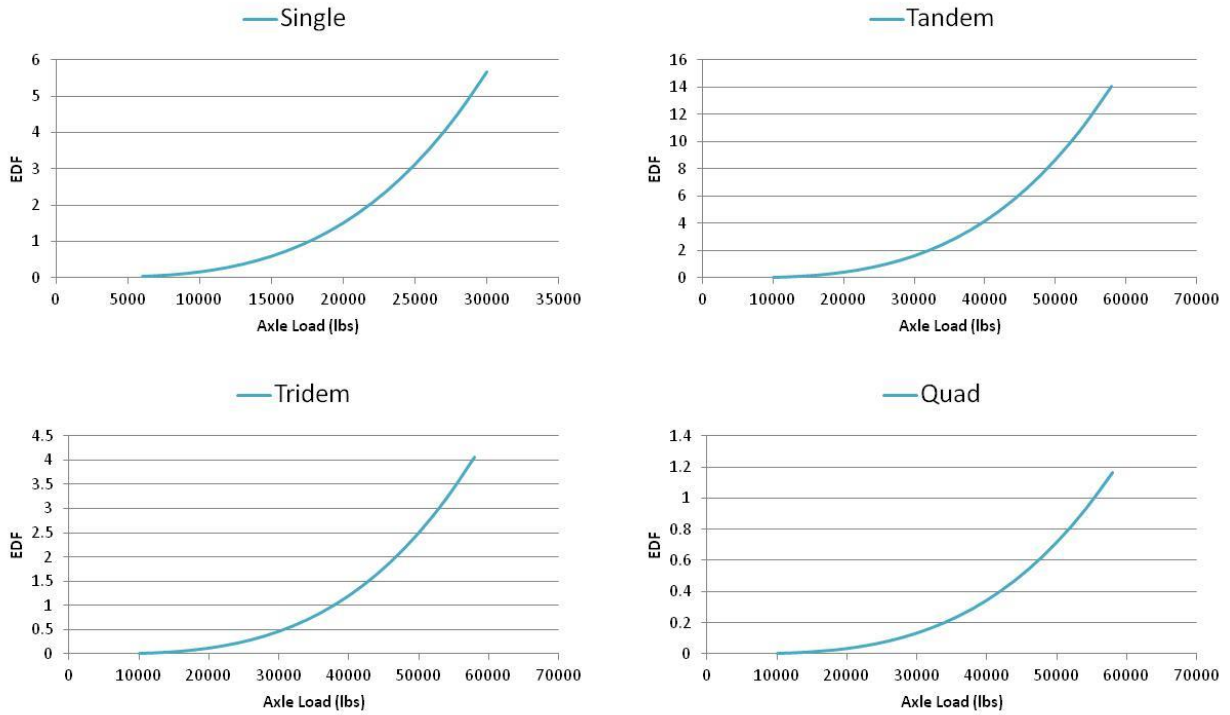
Figure 13: EDFs calculated using punchout failure criteria
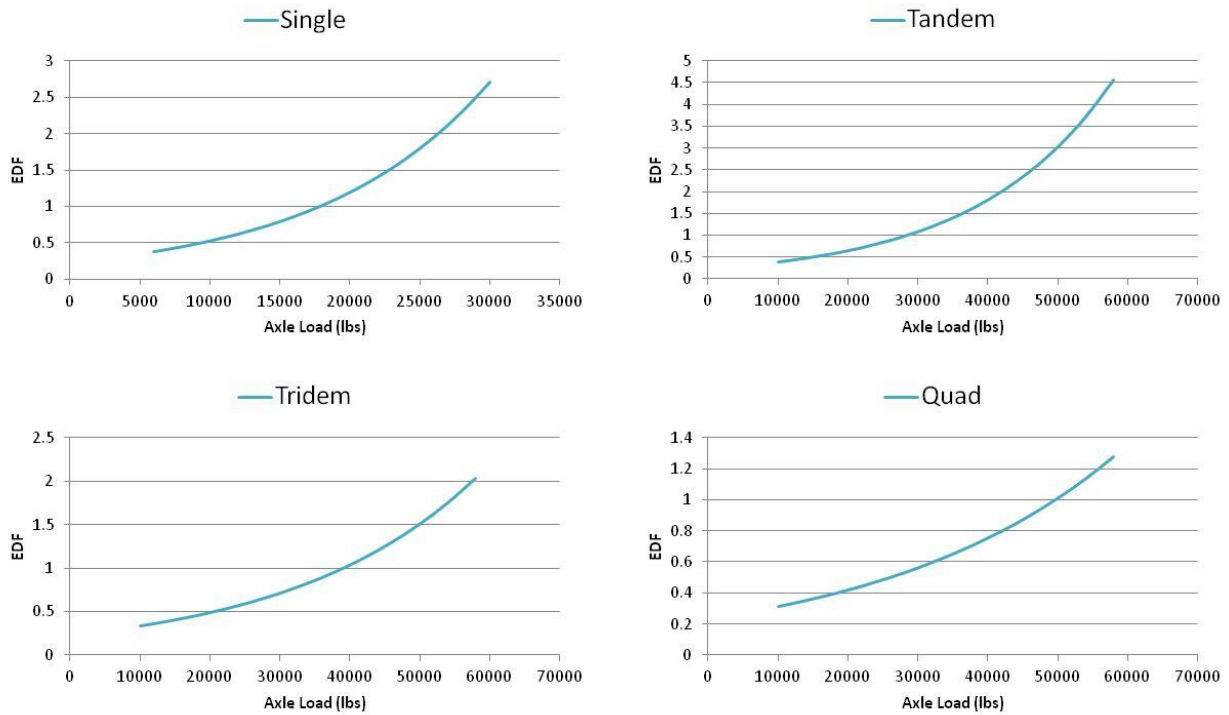
Figure 14: EDFs calculated using roughness failure criteria

Figure 15 shows the EDFs computed for Class 9 and Class 10 trucks and demonstrates the benefit associated with the additional axle in the case of the later. The specific example also illustrates that the EDF approach presented in this paper could be used by the industry to determine axle configuration and loads that are friendlier to the pavement structure in order to minimize pavement damage and, therefore, result in lower OS/OW permit fees.

Figure 15: EDFs calculated for FHWA Class 9 and Class 10 Trucks

Conclusions

This chapter presents a methodology for determination of the load equivalencies for different axle and load configuration on rigid pavements to be applied for OS/OW vehicles. The methodology uses a modular architecture that focuses on determining the equivalent damage factors (EDFs) for different axle loads and configurations, which can subsequently be added to establish the EDF of any vehicle. The EDFs evaluated as part of this study focused on two primary d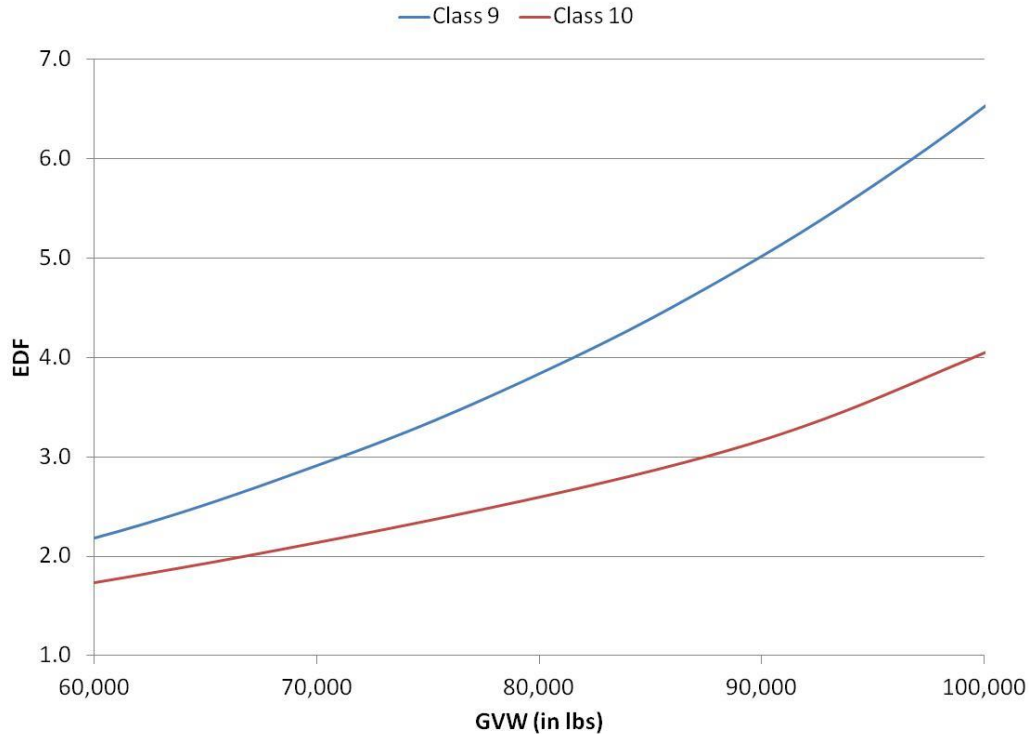istress mechanisms applicable to CRC pavements – punchout and roughness. It was observed in either of the two cases that the ALF and the slab thicknesses were uncorrelated, which led the study team to obtain gross averages for the same. It was interesting to note that the GEFs calculated using either of the failure criteria closely resembled each other.

The ALF computed for CRC pavement sections using the punchout criteria was about 3.3. Although this implies that it is slightly lower than the widely accepted value of 4.0, it still suggests that the results are in tandem with the power law. However, the methodology proposed herein is wider in application and scope because it uses multiple-failure criteria. Besides, it is more accurate and reliable as it is based on the recently developed DARWin-ME.

The final section of this chapter shows how to use the models suggested in this paper in determining load equivalencies for OS/OW permits or for any vehicle in general. The example provided indicates that, for a given GVW, the distribution of loads and axle configuration greatly affects the EDFs. The methodology described in this paper could be used to optimize the

distribution of the payload and the axle configuration to minimize infrastructure damage and to reduce potential OS/OW permit fees.

CHAPTER 4 – CONCLUSIONS & RECOMMENDATIONS

Summary & Conclusions

Recent developments in the oil and gas energy sector in Texas have resulted in increased volumes of traffic with an associated increase in the road deterioration rate. This unanticipated and accelerated deterioration imposes additional burden on already insufficient maintenance and rehabilitation budgets that affect most state highway agencies in the United States. There is absolutely no doubt that the energy sector contributes immensely to the economy of the state and the region, but it is also a fact that it is not sustainable to keep the highway system in a state of good repair. This project attempted to quantify the problem.

A mechanistically-based methodology was developed and utilized to estimate the damage caused to the surface transportation infrastructure. This study used the DARWin-ME design guide and software. The outcome of the mechanistically-based analysis produced the rational for establishing the proportion of damage that can be attributed to the oversize and overweight traffic generated by the oil and gas industries and can be used to establish costs for addressing reconstruction, rehabilitation and maintenance needs. With the elements developed from the previous steps, a management system can be proposed that will enable the State Highway Agencies in the region and local authorities to make better utilization of their limited resources.

The first portion of this study (chapter 2) presents a methodology for determination of load equivalencies for different axle configurations and loads on flexible pavements using mechanistic-empirical design procedures. The focus was on oversize/overweight (OS/OW) vehicles. The study uses the DARWin-ME system for pavement analysis and computation of Equivalent Damage Factors (EDF). In the context of this study, the EDF for a given axle load and configuration consists of two partial factors: Axle Load Factor (ALF) and Group Equivalency Factor (GEF). The framework adopted in this study defines a given axle load and configuration equivalent to a reference axle load based on equivalent pavement responses that results in the same distress level. The study uses a modular approach towards determination of the EDF for different vehicle configurations. The load equivalency for a given truck configuration is equal to the sum of the EDF of its constituent axles. To that effect, the EDF for single, tandem, tridem and quad axles were evaluated over a wide spectrum of varying loads using three different failure criteria: rutting, fatigue cracking and roughness. This provided the basis for developing the models for predicting the EDF of any given axle configuration for any given load.

Except for the case of rutting, there was no evidence suggesting that the EDFs are affected by the structural capacity of the pavement sections. In the case of single axles, however, the structural capacity had an inverse relationship with the EDFs, which suggests that thicker pavement structures are less sensitive to traffic loads. In the case of tandem, tridem and quad axles, the relationship was non-monotonic with the EDFs reaching their peak for structural

numbers between 3.5 and 4.0. In the case of fatigue cracking, it was observed that even though the structural number did not clearly influence the EDFs, there is a linear relationship between the ALF and the number of axles per axle group. Finally in the case of roughness, the EDFs did not show any systematic trend for different structural numbers, which led the study to propose an average ALF that is independent of the axle group or the structural capacity of the pavement section.

The second portion of this study (Chapter 3) focused on developing a methodology to establish load equivalencies between OS/OW loads based on the concept of equivalent damage using Mechanistic-Empirical design procedures for rigid pavements, more specifically for CRC pavements. In the context of this study, a particular load that results in similar response (or pavement performance) as that of a reference load is considered as equivalent. The study focuses on two different failure mechanisms – roughness and punchouts, for the determination of the equivalent damage factors (EDF). Furthermore, the study introduces the partial factors – axle load factor (ALF) and group equivalency factor (GEF), and attributes the EDF for any given axle load and configuration to these two factors. Given that pavement responses are largely influenced by climatic and site-specific features, the study team analyzed a number of CRC pavement sections that were sampled across the state of Texas so that there is a good representation of sections from each of the five different climatic regions.

Results showed that for punchout failures there is a linear relationship between the normalized load and the EDF on a log-log scale. However, there was no noticeable evidence suggesting a relationship between the ALF and slab thickness. Following this observation, the study team obtained a gross average ALF that is independent of the different axle groups and slab thicknesses.

In the case of roughness, an exponential relationship was employed in capturing the relationship between the EDF and the normalized load. Just as with the punchout failure, the ALF and slab thickness were found to be uncorrelated. Therefore, an average ALF was computed.

Recommendations

The models suggested in this study could be used in determining load equivalencies for OS/OW permits or for any vehicle in general. For a given GVW, the distribution of loads and axle configuration greatly affects the EDFs. The methodology described in this paper could be used to optimize the distribution of the payload and the axle configuration to minimize infrastructure damage and to reduce potential OS/OW permit fees.

Possible Applications

A management system developed as a result of this study will aim at developing a sustainable solution to manage the surface transportation system affected by the energy developments in an efficient manner with the goal of enhancing the economic prosperity of the region and improving

the quality of life of the inhabitants of the region. The SHA and local authorities will have a system that will facilitate the implementation of preventive maintenance strategies (pro-active) as opposed to rehabilitation strategies (re-active).

Short Comings & Further Research

Contact stress was not considered in this study and should be considered for future research. The experimental design of this study did not consider the effect of tire pressures, limiting that factor to 120 psi. The tire pressure is what governs the contact pressure, and it can be changed in the software, which will generate different damages.

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