

# Determining the Consumption of OS/OW Vehicles Using Mechanistic-Empirical Principles

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**ABSTRACT:** This study focuses 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 CRCP 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.

**KEY WORDS:** Mechanistic-Empirical, EDF, oversize, overweight, roughness, Darwin ME

## 1 INTRODUCTION

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 4 ft 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).

This 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 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. 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. The primary objective of this study is, therefore, to establish 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.

The study focuses on investigation of the equivalent damage due to individual axles because conventional wisdom indicates that “pavements feel axle loads, not gross vehicle loads.” The proposed methodology is beneficial because it allows the adoption of a modular approach to calculate 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).

## 2 BACKGROUND

A literature review of this subject revealed the following terminologies: Load Equivalency Factor (LEF) and Equivalent Damage Factor (EDF), which have been used interchangeably. Although both of these terms carry similar meaning, the former was introduced after the findings of the AASHO Road Test in the 1960s while the latter was developed as a generalization of the LEF concept, as it incorporates multiple failure criteria and is mechanistically based (3). A number of factors that were traditionally combined into one single coefficient (LEF) are now assessed individually by means of partial factors. To date, three partial factors have been developed but assessing other aspects (such as loading rate, aging conditions, etc.) is possible. Prozzi et al. (4, 5) suggested the following relationship for determination of  $EDF_L$  for a particular axle load, configuration, and tire pressure:

$$EDF = GEF \times ALF \times CSF \quad (1)$$

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 life of the pavement under a single axle to the life of the pavement under a group of axles, e.g., tandem, tridem, or quad. The load of the individual axles of the group should be the same as the load of the single axle. This factor takes into account only 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 1.

Axle Load Factor (ALF) is defined as the ratio between the life of the pavement under a single axle of 18 kips and the life of the pavement under a single axle of different load. The name ALF is proposed because this factor takes into account only 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. (4, 5) aims to establish the EDF for different axle loads and configurations through quantification of each of these partial factors. However, this study adopts a reverse approach wherein the EDF is determined first, followed by subsequent decomposition into ALF and GEF. Note that the experimental design of this study did not consider the effect of tire pressures, limiting that factor to 120 psi.

### **3 METHODOLOGY**

#### **3.1 Calculation of EDF**

As outlined in the foregoing discussion, this study 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 equivalencies, 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 (6). 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 kind of rigid pavement that is constructed today is CRC pavements. Therefore, the authors 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 (7). During the 1970's and early 1980's, CRCP 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 CRCP the same thickness as JPCP (8). 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 CRCP are caused by excessive wheel loading applications and insufficient structural capacity of the CRCP, such as deficient slab thickness (design issue) or sub-base support (design/construction issue). It manifests as 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 CRCP. 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.

As suggested earlier, the 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 with EDFs greater than 1 will need less than 30 years. Following is the equation used for calculation of the EDF in the study:

$$EDF = \frac{N_{18}}{N_L} \quad (2)$$

$N_{18}$ : 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 (9). 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:

$$LEF = \frac{N_{18}}{N_L} = \left( \frac{W_L}{W_{18}} \right)^\alpha \quad (3)$$

$W_L$  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 suggests a linear relationship between LEF and the normalized load in a log-log scale, the slope of this linear relationship being equal to ' $\alpha$ ' 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 (6). 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.

### **3.2 Mechanistic-Empirical Pavement Analysis**

The DARWin-ME software, which was used for pavement distress simulation in this study, 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 (10).

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.

### **3.3 Experimental Design**

As highlighted earlier, the literature suggests that the EDF for any given axle load and configuration depends to some extent on the structural capacity of the highway facility (3, 4). 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 1).

**TABLE 1: 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 2 summarizes the range of axle load and configurations included in this study.

**TABLE 2: Simulated axle loads and configurations**

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

### 3.4 Determination of EDF for Punchouts

Equation 3 suggests the possibility of establishing a linear relationship between the EDF and the normalized load on a log-log scale. Figure 1 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 1).

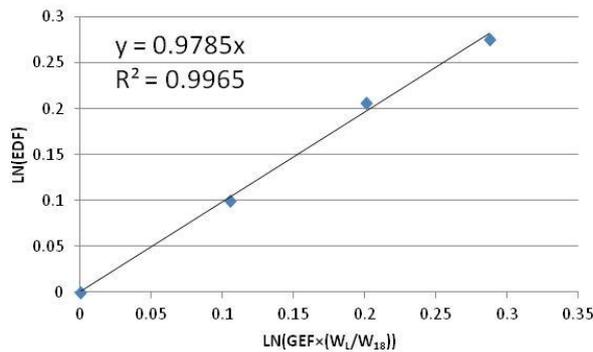
The fact that the slope of the line differs from section to section indicates that the EDF for any given axle load and configuration is influenced by the structural capacity of the highway facility. For tandem and tridem axles, the GEF was introduced for establishing the EDF. As discussed previously,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

$$\ln(EDF) = \alpha \times \ln\left(\frac{W_L}{\beta \times W_{18}}\right) \quad (4)$$

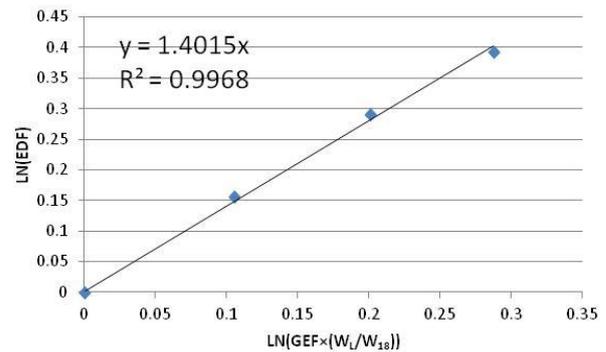
$\alpha$  : ALF, and  
 $\beta$  : GEF.

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 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:

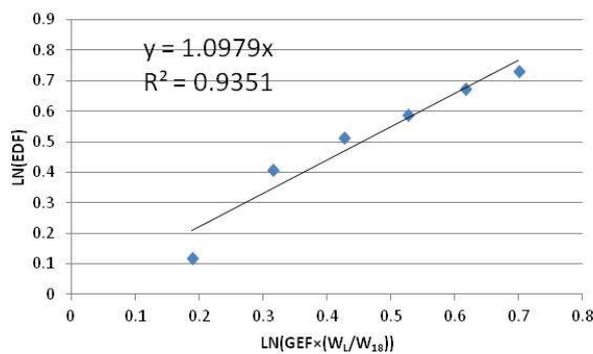
- Tandem Axles: 1.38
- Tridem Axles: 2.14



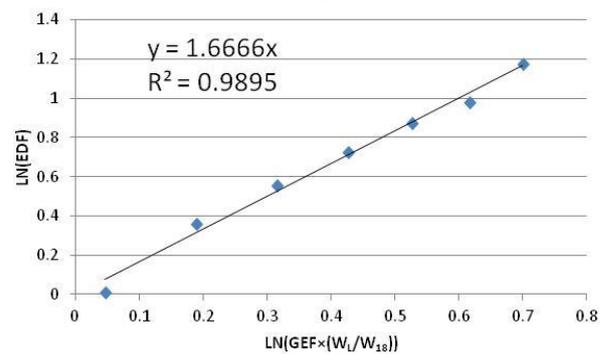
Section 01, Single Axles



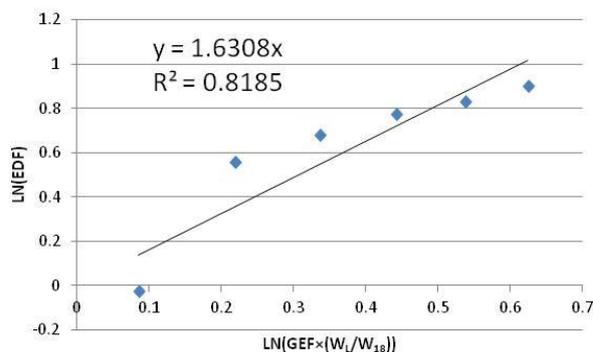
Section 02, Single Axles



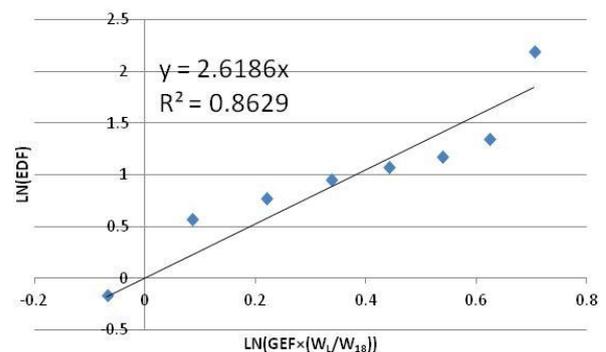
Section 01, Tandem Axles



Section 02, Tandem Axles



Section 01, Tridem Axles



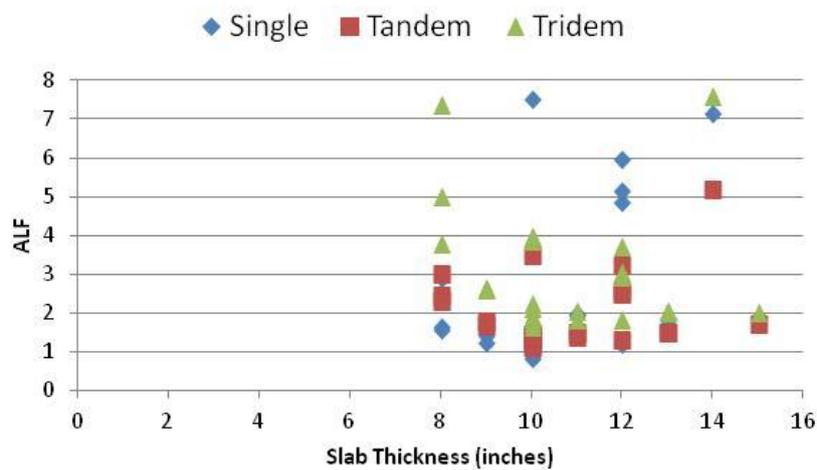
Section 02, Tridem Axles

**FIGURE 1: EDFs based on Punchout Criterion**

Figure 1 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 authors 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 2). 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 2: 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:

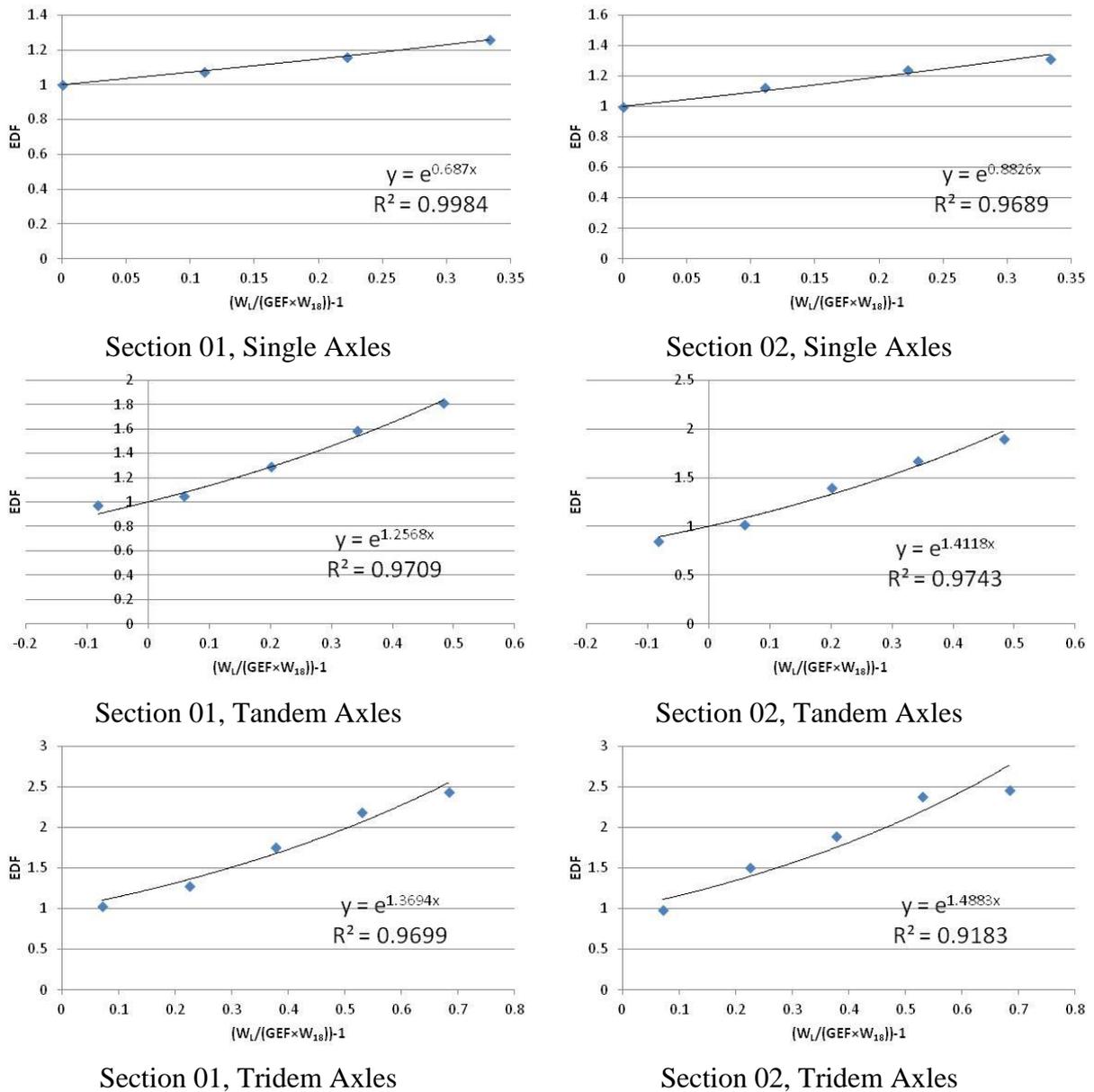
$$\ln(EDF) = (3.27) \times \ln\left(\frac{W_L}{GEF \times W_{18}}\right) \quad (5)$$

### 3.5 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 2, 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 3 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:

$$EDF = e^{ALF \times \left( \frac{W_L}{GEF \times W_{18}} - 1 \right)} \quad (6)$$



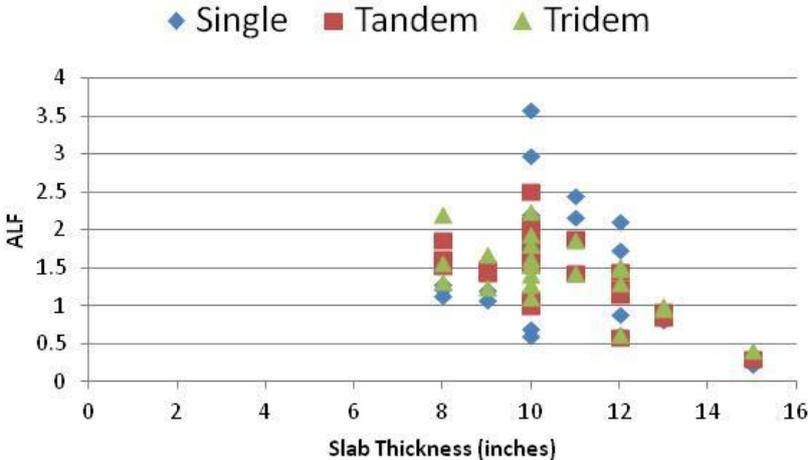
**FIGURE 3: EDFs based on Roughness Criterion**

Although Figure 3 suggests that there is a relationship between these two parameters, the exponents thereof vary considerably. As previously stated, the particular observation might be 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 4). 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 authors 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



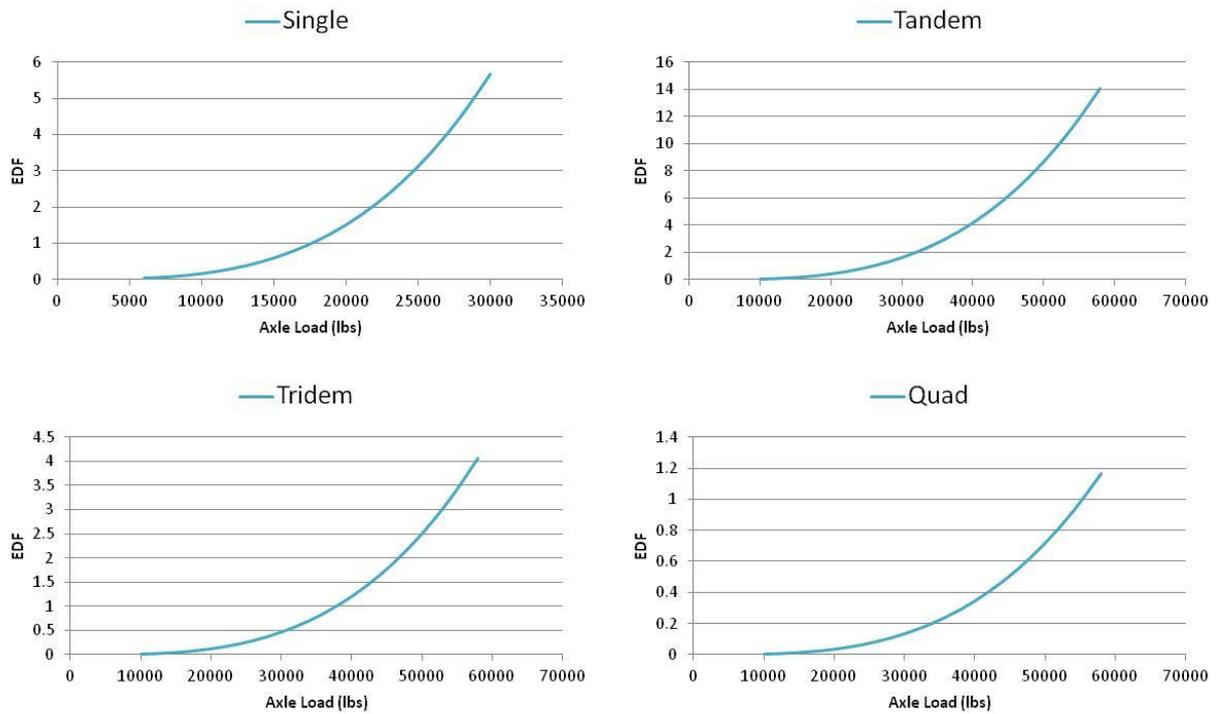
**FIGURE 4: Axle Load Factor using the Roughness Failure Criteria**

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

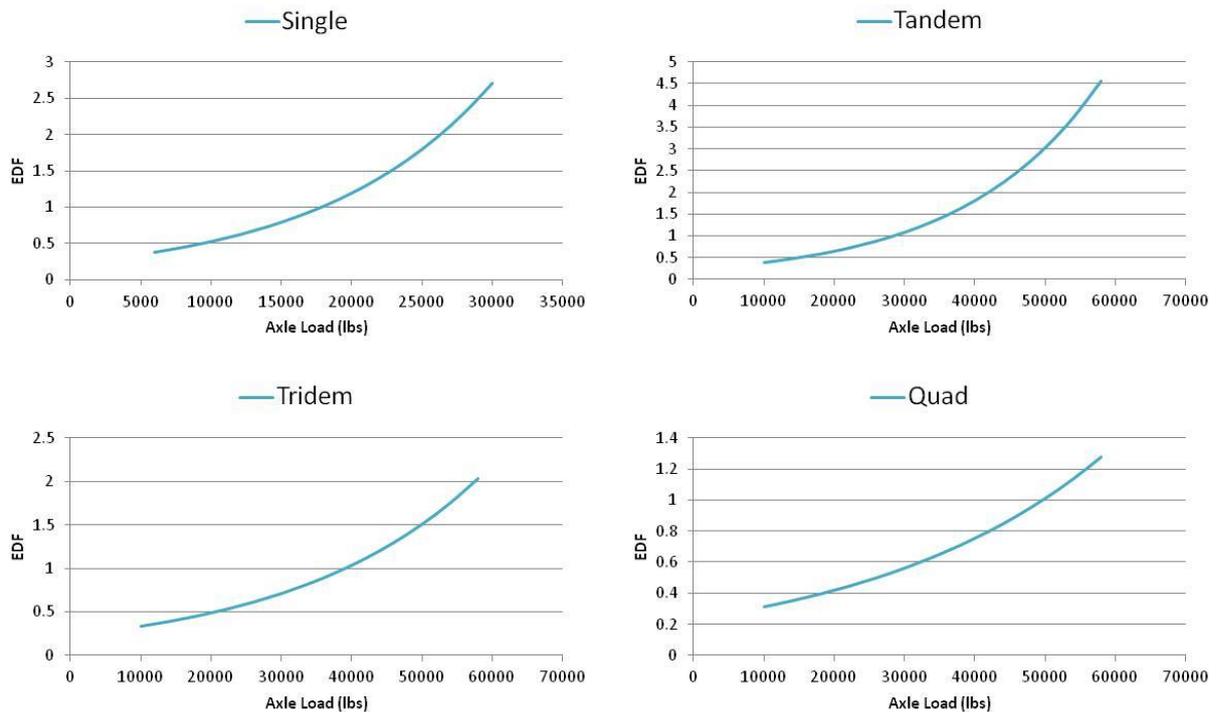
$$EDF = e^{1.46 \left( \frac{W_L}{GEF \times W_{18}} - 1 \right)} \tag{7}$$

**4 APPLICATION**

Figures 5 and 6 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.



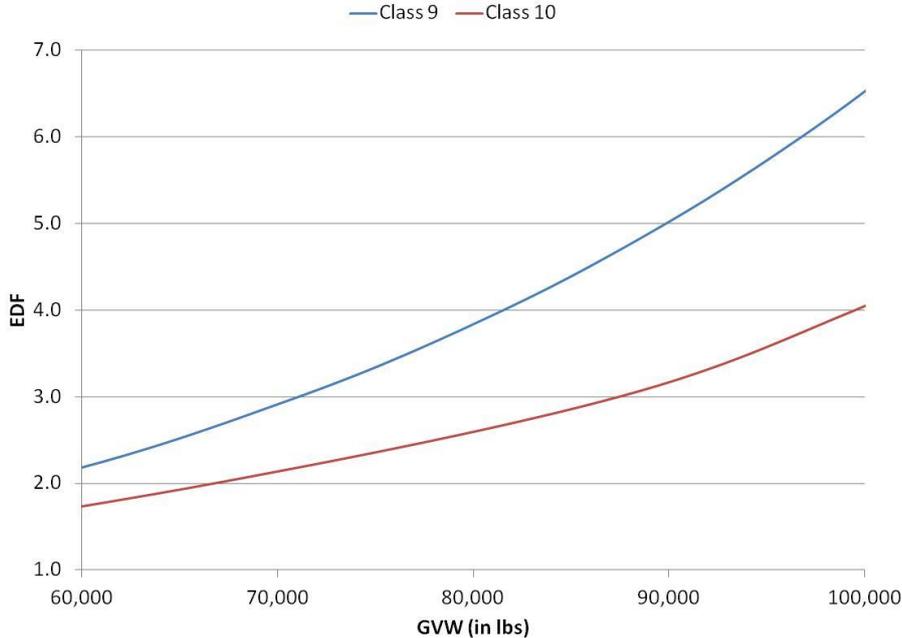
**FIGURE 5: EDFs calculated using punchout failure criteria**



**FIGURE 6: EDFs calculated using roughness failure criteria**

Figure 7 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 7: EDFs calculated for FHWA Class 9 and Class 10 Trucks**

## 5 CONCLUSIONS

This paper 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 distress 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 paper 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.

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