NDOT Research Report

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Mechanistic-Based Pavement Damage Associated Cost from Oversize and Overweight Vehicles in Nevada

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Disclaimer

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16. Abstract

The movement of overweight (OW) vehicles has become more common over the years due to its vital necessity for many important industries such as chemical, oil, defense, etc. Using OW vehicles reduces the number of vehicles on highways, potentially decreasing traffic congestion and emissions. However, the operation of large and heavy vehicles can lead to a speedy deterioration of the roadway system; hence necessitating additional resources to maintain the conditions of roadway pavements at an acceptable level.

The approach presented in this report allows for the estimation of pavement damage associated costs (PDAC) attributable to OW vehicle moves. The PDAC can be estimated for different OW axle loadings and configurations with due considerations given to locally-calibrated pavement distress models, existing pavement condition, different pavement repair options, and vehicle miles traveled (VMT). The approach uses the same information currently requested by NDOT during the OW permit application process and provides a realistic methodology to assess pavement damage from single-trip and multi-trip OW scenarios. In the methodology, the damage from OW vehicles is compared to that caused by a standard vehicle. It should be noted that the costs associated to the pavement damage caused by lighter vehicles (GVW up to 80,000 lb) is assumed to be already covered by fuel taxes and will be reflected in a PDAC of zero dollars.

As part of this study a ten-year NDOT over-dimensional permit database containing 367,595 entries was analyzed. Along with the ten-year permit database, thousands of actual over-dimensional permit forms which described GVW and the entire axle and load configurations of the permitted vehicles were analyzed. The purpose of the analysis was the identification and classification of trends, GVW, axle loads/tire loads and other important characteristics of the OW movements in Nevada. This analysis enabled the design of a comprehensive experimental plan of pavement analyses required to model OW vehicles under the different loading, pavement temperature, and speed conditions found in Nevada.

The presented methodology provides useful ways to assess pavement damage from OW vehicles, eliminating the need for conducting individual deterministic pavement analysis assessments. Through comparative analysis it was found that the proposed methodology produces PDAC values that are comparable to those levied by other SHAs that implement distance and weight-distance fee structures. It was also estimated that the PDAC methodology could produce significant increase in revenue when assuming average input values. However, such increase in revenue is mostly associated to OW vehicles in the heaviest categories.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ACRONYMS AND SYMBOLS

ABBREVIATIONS AND ACRONYMS

3D	Three-Dimensional
AADTT	Average Annual Daily Truck Traffic
AASHTO	American Association of State Highway and Transportation Officials
AASHO	American Association of State Highway Officials
AC	Asphalt Concrete
BRT	Bus Rapid Transit
CAB	Crushed Aggregate Base
CDF	Cumulative Distribution Function
ESAL	Equivalent Single Axle Load
FCVM	Finite Control Volume Method
FE	Finite Element
FHWA	Federal Highway Administration
GAWR	Gross Axle Weight Rating
GVW	Gross Vehicle Weight
HCAS	Highway Cost Allocation Study
LCV	Longer Combination Vehicle
LEF	Load Equivalency Factor
LR	Life Reduction
LTPP	Long Term Pavement Performance
MC	Monte-Carlo
ME	Mechanistic-Empirical
MEPDG	Mechanistic-Empirical Pavement Design Guide
NAPCOM	National Pavement Cost Model
NCHRP	National Cooperative Highway Research Program
NDOT	Nevada Department of Transportation
ODOT	Ohio Department of Transportation

OVAP	Overweight Vehicle Analysis Package
OW	Overweight
PaveDAT	Pavement Analysis Tool
PDAC	Pavement Damage Associated Costs
PDF	Probability Distribution Function
PMS	Pavement Management Systems
PWV	Present Worth Value
RBM	Road Bed Modification
SG	Subgrade
RSL	Remaining Service Life
SHA	State Highway Agency
SHL	Superheavy Load
SOV	Shorter Overweight Vehicle
STD	Standard
SG	Subgrade
Teff	Effective Pavement Temperature
UNR	University of Nevada, Reno
US	United States
VMT	Vehicle Miles Traveled

SYMBOLS

E	AC layer dynamic modulus
T	AC layer temperature
k_{r1}	AC permanent deformation calibration factor
k_{r2}	AC permanent deformation calibration factor for temperature exponent
k_{r3}	AC permanent deformation calibration factor for number of load repetitions exponent
β_{r1}	AC permanent deformation local calibration factor
β_{r2}	AC permanent deformation local calibration factor for temperature exponent

β_{r3}	AC permanent deformation local calibration factor for number of load repetitions exponent
$\Delta N_{std:eq}$	Additional passes of the equivalent reference vehicle to cause $d_{truck:eq+1}$
Rain	Annual cumulative rainfall depth
ε_a	Axial strain
z	Critical depth
$d_{truck:eq+1}$	Damage caused by an extra pass of superheavy vehicles after $N_{truck:eq}$
d_{Nstd}	Distress after specific number of vehicle passes
T_{eff_Rut}	Effective pavement temperature for AC rutting
T_{eff_fat}	Effective pavement temperature for AC fatigue cracking
k_{f1}	Fatigue cracking calibration factor
k_{f2}	Fatigue cracking calibration factor for tensile strain exponent
k_{f3}	Fatigue cracking calibration factor for stiffness exponent
β_{f1}	Fatigue cracking laboratory calibration factor
β_{f2}	Fatigue cracking laboratory calibration factor for tensile exponent
β_{f3}	Fatigue cracking laboratory calibration factor for stiffness exponent
Freq	Frequency of loading
ε_t	Maximum tensile strain at bottom of AC layer
MAAT	Mean annual air temperature
Sunshine	Mean annual percent sunshine
Wind	Mean annual wind speed
N_f	Number of load applications to fatigue cracking failure
N_r	Number of load applications to AC permanent deformation failure
$N_{truck:eq}$	Number of superheavy vehicle passes to cause same distress as d_{Nstd}
$N_{failure}$	Number of OW vehicle or reference vehicle passes to the threshold failure
$N_{i:failure}$	Number of passes to threshold failure for the individual axle groups within the OW vehicle or reference vehicle
Ln	Natural logarithm
%	Percentage

ε_p	Plastic strain
$N_{std:f}$	Predicted number of reference vehicle passes to failure
$N_{SHL:f}$	Predicted number of superheavy vehicle passes to failure
M_R	Resilient modulus
ε_r	Resilient strain
$\sigma MMAT$	Standard deviation of mean annual air temperature

CHAPTER 1 INTRODUCTION

1.1 Overview

With the significant and continuous growth of freight transportation, state highway agencies (SHAs) are challenged to maintain the highway infrastructure at an acceptable level of service.[(1)] One approach to reduce the number of commercial vehicles on the highway network is allowing the operation of multi-trailer vehicles. Multi-trailer vehicles make it possible for shippers to accommodate larger and heavier cargo in a haul that would otherwise require multiple shipments. However, multi-trailer units cannot be used for large non-divisible loads, thus freight companies use oversize and overweight (OS/OW) vehicles to transport larger and heavier-than-standard loads.

Per federal law, the commercial vehicle gross vehicle weight (GVW) standard limit is currently 80,000 lb for the interstate highway network.[(2, 3)] This statute is generally applied and enforced by SHAs in the nation. This GVW limit and other axle loading statutes are used to regulate highway traffic loadings and prevent premature deterioration which could drastically increase costs of pavement maintenance and rehabilitation. In addition, the operation of large and heavy vehicles can lead to a speedy deterioration of the roadway system; hence necessitating additional resources to maintain the conditions of the roadway pavements at an acceptable level. As part of this study, a cost allocation methodology was recommended to determine the extent of pavement damage and costs attributable to OW movements on flexible pavements. The quantification of increased costs due to repair and maintenance activities attributable to OW movement is very helpful to engineers and practitioners so that informed decisions on the issuance of OW permits can be made.

The Nevada Department of transportation (NDOT) classifies OS/OW vehicles based on their GVW, length, width, and height into either over dimensional vehicles (ODV), shorter overweight vehicles (SOV) and longer combination vehicles (LCV).[(4)] Table 1.1 summarizes NDOT's classification for OS/OW vehicles. It should be mentioned that all vehicles in this table are required to obtain an over-dimensional permit to operate on Nevada's roadways. In fact, NDOT issues special permits to allow the operation of these vehicles and collect a nominal fee of $25 to allow their legal operation on the highway system. NDOT issued more than 300,000 OS/OW permits from 2004-2013. It should be noted that not all permitted vehicles have a GVW greater than 80,000 lb (e.g., oversize vehicle permits). Vehicles having GVW lower than a fully loaded-standard truck (80,000 GVW) are excluded from this study.

Table 1.1. Characteristics of OS/OW Vehicles in Nevada.

Vehicle Classification	Description
Over Dimensional Vehicle (ODV)	Exceed 80,000 lb GVW
	Exceed 8 feet, 6 inch in width
	Exceed 14 feet in height
	Exceed 10 feet of front of rear overhang
	Exceed 70 feet in length
Shorter Overweight Vehicle (SOV)	Exceed 80,000 lb GVW
	Do not exceed 70 feet in length
Longer Combination Vehicle (LCV)	All divisible vehicles loads that Exceed 70 feet in length

1.2 Problem Statement

Quantifying pavement damage attributable to OW vehicles is a challenging task. An array of factors specific to each OW movement (e.g., axle and tire loadings and configurations, traveling speed, temperature and properties of existing pavement layers at the time of the move, etc.) influences the magnitude of the load-induced pavement damage. The potential damage caused by operation of OW vehicles is generally not considered in the new and rehabilitation designs of pavement structures. Since heavier axle loads of OW vehicles can introduce greater stresses and strains in the pavement compared to those estimated under a traditional truck loading, a single OW vehicle pass could induce the same damage as multiple passes of a standard heavy vehicle; herein referred to as “reference vehicle.” Thus, leading to a faster deterioration in the pavement condition as compared to the anticipated deterioration rate under the standard design traffic. This is highly influenced by the structural capacity of the existing pavement as well as the climatic conditions at the time of the OW movement.

Other challenges associated with determining pavement damage due to an OW movement is properly accounting for the characteristics of the existing pavement layers at the time of the move. For instance, the viscoelastic property of the asphalt concrete (AC) layer influences the load-induced pavement responses, thus pavement damage associated with the OW movement. For example, pavement damage caused by an OW vehicle operating during the summer (or even daytime hours) may be significantly different than the damage caused by the same vehicle operating during a different season (or during nighttime hours of the same day).

As a result, engineers and transportation officials need reliable tools to evaluate and assess pavement damage and associated costs attributable to OW vehicles operating under different loading and environmental conditions. As part of this NDOT project, a methodology was adopted to determine the extent of pavement damage and associated costs attributable to OW vehicle movements in Nevada.

The evaluation presented in this report addresses pavement damage and pavement damage cost attributable to OW vehicles only. The costs associated to the pavement damage caused by lighter vehicles (GVW up to 80,000 lb) is assumed to be already covered by fuel taxes and will be reflected in a PDAC of zero dollars.

1.2.1. Pavement Damage from Multi-trip OW Vehicles

OS/OW permits can be issued as single-trip or multi-trip (monthly, seasonal or annual) permits. Generally, single-trip permits allow the movement of a specific OW vehicle for a single pass within a duration of a few select days. On the other hand, multi-trip permits authorize a specific OW vehicle to operate without restriction for the duration of a permit. Issuance of multi-trip permits eases SHAs permit processing burden, reducing the time and resources needed to process OS/OW permits. However, SHAs have difficulties tracking information associated with multi-trip permits, such as number of trips traveled, vehicles miles traveled (VMT), routes traveled, and date and time of the year when the trips took place. Such information are essential for assessing potential pavement damage attributed to OW vehicle moves operating under multi-trip permits.

Recently, several methodologies have been presented to determine pavement Damage Associated Costs (PDAC) attributed to OW vehicles.(5, 6, 7, 8) These methodologies have only been developed for single-trip scenarios using deterministic analysis. Currently there is no approach available in the literature addressing multi-trip scenarios. The lack of such an approach leads to a high degree of uncertainty associated with assessing PDAC due to multi-trip OW vehicles.

1.3 Overall Research Objective

The objective of this study is to: (1) assess pavement damage attributable to OW vehicle moves in Nevada, and (2) provide a framework for a permit fee structure of single and multi OW trips in Nevada. The methodology employed is based on mechanistic-empirical (ME) analysis of flexible pavements under OW vehicle loadings utilizing pavement performance models that have been locally calibrated to Nevada conditions. The presented methodology uses information that are currently collected by the NDOT over dimensional office during the permit application process and addresses pavement damage and associated costs from single and multi-trip permitted vehicles. For instance, the PDAC for single OW trips is based on a deterministic analysis using specific set of input factors provided by the freight company during the OS/OW permit application process. On the other hand, the pavement damage from multi-trip permitted vehicles was addressed based on a probabilistic analysis using Monte-Carlo (MC) simulations, which yields to PDAC distributions.

The approach presented in this study considers potentially influential critical factors during the duration of the permit. Such factors include axle load and configuration, pavement structure, associated material properties, and environmental conditions encountered during a permit period.

A 10-year (2004-2013) OS/OW permit database was utilized to obtain the required information and develop a tool package for analyzing pavement damage and PDAC from single and multi-trip permits instantaneously without the need for a lengthy analysis and calculation process.

1.4 Organization of Report

Background information about the current OW permitting practices in the United States (US) and information related to pavement damage and PDAC are first presented in Chapter 2. The adopted cost allocation methodology used in this research study is also presented in Chapter 2. Next, the review and analysis of the electronic database for historical over-dimensional permits along with thousands of over-dimensional permit forms are summarized in Chapter 3. Details on the development of the database of critical pavement responses that is essential for the PDAC analysis are presented in Chapter 4. Chapter 5 summarizes the deterministic and probabilistic analysis of pavement damage and PDAC. The description of a practical and user-friendly tool package in Microsoft Excel®, namely *Overweight Vehicle Analysis Package*, for the analysis of different single-trip and multi-trip OW vehicles is presented in Chapter 6. Several case studies including single and multi OW trips along with two comparative analyses are then presented in Chapter 7. The first comparative analysis is between the PDAC of an example OW vehicle calculated based on the approach developed in this study and the estimated permit fee for the same OW vehicle imposed by surrounding states. The second comparative analysis is between the estimated annual fees collected by NDOT in 2013 and those estimated using the PDAC developed in this study. Finally, a summary of findings and recommendations for future research are given in Chapter 8.

CHAPTER 2 COST ALLOCATION METHODOLOGY

A review of literature was conducted to provide information on the permit fee structures currently implemented in the nation. The review also included studies related to highway costs allocation and the estimation of pavement damage and PDAC attributed to OW vehicles. Multiple methodologies were found in the literature. Numerous studies implemented empirical methods to address the degradation of flexible pavements due to OW vehicle loading. On the other hand, recent studies suggested the use of ME models to estimate pavement damage. A ME-based cost allocation methodology to estimate pavement damage associated costs attributable to the movement of OW vehicles in Nevada is presented.

2.1 Overweight Vehicle Permitting Practices in United States

The determination of permit fees structures in the US has been the recent focus of multiple studies and reports. This is mainly due to the increasing demand and growth of overweight trucking transportation. In fact, a recent review of current overweight vehicle permitting practices in the US was recently conducted by Papagiannakis.(9) According to the study, while multiple agencies have adopted a GVW and an axle weight-distance permit scheme, others collect flat fees for single-trip permits. The single-trip permit fee ranged anywhere from 25 to 550 dollars, regardless of associated pavement damage or any traveled distance indicators.(9) Another important finding from the recent permit review is that the fees collected by SHAs via OW permits are mainly assigned for administrative costs.(9) SHAs have autonomy to establish permit fee regulation that best feed their local circumstances.

Table 2.1 summarizes the different OW vehicle permit fee structures for different state highway agencies in US based on the study conducted by Papagiannakis.(9) The following summarizes the overall findings from this study.

Table 2.1. Summary of Permit Fee Structures in United States.

Permit Structure Type	US States	Permit Fees Examples
Case by Case	Alabama, Nebraska, Iowa, Rhode Island, Michigan	At least \$20
Weight Only	Colorado, North Carolina, South Carolina, Georgia, Kentucky, Delaware, Maryland, New Jersey, Massachusetts, Vermont, Maine	\$10 per OW axle, \$3 per 1,000 lb after 132,000 lb GVW
Weight – Distance	Washington, Oregon, Utah, New Mexico, Montana, Wyoming, North Dakota, South Dakota, Minnesota, Oklahoma, Missouri, Illinois, Louisiana, Mississippi, Tennessee, Indiana, Ohio, West Virginia, Virginia, Florida	\$0.006 mile per ton \$0.20 mile per ton \$70 plus \$3.5 per 5,000 lb per 25 mile \$0.05 per mile per 1,000 lb \$135 plus \$0.04 per ton per mile after 120,000 lb GVW
Distance only	Arizona, Arkansas	\$12 per trip < 50 miles < \$48 per trip
Fixed Fee	Nevada, Idaho, Alaska, New Hampshire, Kansas	\$25, \$71, \$20, \$50
Damage Related	California, Kansas	Carrier pays damage fees
Other	Texas, New York	Fee per number of counties traversed

Most SHAs used weight-distance permit fee structure by considering tons carried and miles travelled by OW vehicle. However, there are also SHAs that only consider distance traveled or even number of counties traversed (e.g., Texas Department of Transportation). Among the SHAs that employed a weight-distance structure, it was observed that the fee unit range varied from 0.006 to 0.20 US dollar per mile per ton.[9] This is considered a wide range which would produce significantly different permit fees.

Multiple SHAs provide a permit fee on a case by case basis. For instance, Alabama charges a nominal permit fee of 100 US dollar and applies an additional charge specific to the respective OW move. Similarly, Michigan and Nebraska charge extra fees in addition to the 50 and 20 US dollars nominal fee, respectively. The extra charges usually depend on the commodities being transported, vehicle dimensions, and axle configuration characteristics of the OW vehicle.

There are agencies that implement a weight only permit fee structure irrespective of the distance travelled by an OW vehicle. For example, Colorado collects 10 US dollar per overweight axle regardless of the distance travelled. North and South Carolina collect 3 US dollar for every 1,000 lb over 132,000 lb GVW with no further consideration given to the distance travelled. New Jersey only considers weight in their permit and charges a base fee of 10 US dollar plus 5 US dollar for every ton more than 80,000 lb GVW. An addition 5 US dollar per ton is charged on single and tandem axles exceeding weights of 22,400 lb and 34,000 lb, respectively.

Among the SHAs that employed a weight-distance structure, it was observed that a fee unit range and permit fee structures are significantly variable. For instance, Mississippi charges a flat fee plus 0.05 US dollar per mile for each additional 1,000 lb above the legal GVW. Similarly, Ohio charges a flat fee of 135 US dollar plus 0.04 US dollar per ton and per mile in excess of 120,000 lb. On the other side, the state of Washington charges a flat fee of 25 US dollar plus 4.25 US dollar for every mile plus 0.50 US dollar per every 5,000 lb in excess of 100,000 GVW. The variability in permit fee structure would create different permit fees for heavy vehicles traversing several states.

Arizona and Arkansas consider only distance in their permit fee structure. Arizona charges 12 US dollar for single-trip permits for vehicles traveling less than 50 miles and 48 US dollar for vehicles traveling more than 50 miles. Similarly, Arkansas charges a nominal fee of 17 US dollar and extra charges ranging from 8 US dollar to 16 US dollar depending on the distance travelled.

Among those states that charge a single flat fee without consideration of distance travelled and/or axle weight or GVW, Nevada charges 25 US dollar per single trip. Idaho and Kansas charge 71 and 50 US dollar, respectively, with no specific or additional fees. California implements a flat permit fee of 16 US dollar, however, the carrier pays a fee for any infrastructure repairs.[9]

Two states use a permit fee structure that cannot be grouped in any of the aforementioned categories. For instance, New York charges a permit fee ranging from 40 to 360 US dollar depending on the commodity being transported plus an analysis fee depending on the GVW. On the other hand, Texas charges a flat fee of 90 US dollar plus a fee depending on the number of counties being traversed plus a maintenance and supervision fees for superheavy vehicles.[9]

Most states do not provide a particular regulation or structure for the issuance of annual or multi-trips. For instance, Nevada charges 60 US dollar per annual trip permits. While Kentucky charges 500 US dollar per annual permit fee, Missouri and Wisconsin charge fees ranging from 300 to 850 US dollar.

As part of the application process, multiple agencies request or conduct empirical or ME pavement analysis when a superheavy load (SHL) vehicle is involved. SHL vehicles are generally classified as OW vehicles having a GVW greater than 250,000 lb. The main objective of such an analysis is to evaluate the structural adequacy and the likelihood of instantaneous shear failure of a pavement section under the SHL vehicle move. Consequently, the analyses are not focused on determining a permit fee directly associated to the pavement damage produced by a single pass of a SHL vehicle. Therefore, a reliable approach for estimating pavement damage and its associated cost attributable to SHL vehicles while considering various analysis factors is needed.

2.2 Review of Cost Allocation Methods

2.2.1. Highway Cost Allocation Studies

The Federal Highway Administration (FHWA) and many SHAs regularly conduct highway cost allocation studies (HCAS) to evaluate highway-related expenses attributable to different vehicle classes and to establish highway cost responsibility.(10) The most common methods of costs allocation are: incremental, proportional, benefit-based, marginal, and costs occasioned approach. The goal is to assign a fair cost share responsibility to the different highway users.

In the incremental approach, the costs of operating, maintaining, rehabilitating, and constructing highway facilities for the lightest highway users are compared to the costs of keeping the facilities to larger and heavier traffic classes. The increments in costs associated to heavier vehicle are known as incremental costs. Incremental methods are designed to distribute the costs associated to light vehicles among all vehicle classes in proportion to the highway usage while, only heavier vehicle classes pay for the incremental costs.(10) After 1982 an updated version of the incremental method was conducted in different states. That updated version was called Federal cost allocation method and it is a form of the incremental method with adjustments for some of the expenditures elements in the process.(10) The Federal method is based on a consumption principle applied to pavement rehabilitation activities. Also at the same time, a traditional incremental approach is implemented for some other expenditure elements.

The proportional method distributes highway costs based on vehicle characteristics by using a cost allocator factor such as equivalent single axle load (ESALs) and/or VMT. Based on this approach common construction and maintenance highway costs are distributed proportionally; the higher the VMT or the ESALs the higher the cost share.(10)

In the benefit-based approach, the benefits are tied to the use of the highway system. Therefore, not only the direct users of the roadway are responsible for the costs, but also all of those who benefit directly from the roadway system. This approach presents several challenges because it is challenging to distinguish non-highway user benefits.(10)

In the marginal approach, social costs or added costs related to vehicle trips are associated with highway usage. Charges such as, air pollution costs, traffic congestion, noise, marginal pavement costs and other related expenditures are charges to the highway user.(10) The marginal approach is usually considered when the total or overall highway expenditures are needed. Because of the inclusion of marginal costs to users it is estimated that this method would estimate higher costs to users.(11)

The Federal method is based on a consumption principle applied to pavement rehabilitation activities. Also at the same time, a traditional incremental approach is implemented for some other expenditure elements. This method has been implemented to estimate pavement damage costs from heavy traffic. The cost of constructing a pavement structure that incrementally includes heavier traffic classes is regularly conducted.(10)

In the Cost-occasioned approach, highway and most particularly, pavement damage costs from OW vehicles' traffic has been estimated using cost occasioned approaches. In this method, the highway user pays the cost it creates. In this approach the maintenance, repair, and construction costs can be individually distributed to the respective highway users.(10, 11)

2.2.2. National Pavement Costs Model

The National Pavement Cost Model (NAPCOM) is a product of a refined Federal method. In this methodology, increments are categorized as load-related and non-load-related costs. The costs associated to axle loads are obtained through evaluations of different pavement damage models using ME approaches. According to Balduci et al., NAPCOM was developed because traditional approaches using simplistic ESALs did not present good correlations with empirical pavement damage data.(10113) The models that NAPCOM is based on considered, among other factors, climatic variations as well as distinct levels of traffic and loads.

NAPCOM has evolved over the years and led to the implementation of simplified models such as the Pavement Analysis Tool (PaveDAT).(12, 13) This spreadsheet tool uses the same data and relies on the same concepts of NAPCOM to calculate the pavement associated cost for a specific vehicle trip. However, PaveDAT cost models are based on nationally calibrated performance models for typical distresses in flexible pavements that were developed under the National Cooperative Highway Research Program (NCHRP) project 01-37A. These distress performance models are mostly applicable to flexible pavements built with dense-graded unmodified AC mixtures.(14) Furthermore, traffic loading input for PaveDAT has to follow the FHWA standardized vehicle classification, thus limiting its use with non-standard vehicles such as those used during an OW movement.

2.2.3. Review of Pavement Damage from OW Vehicles and Associated Cost Studies

Truck traffic is one of the most important factors when designing pavement structures. As the GVW and axle loads increase, pavement damage increases significantly. In recent years, heavier and larger truck vehicles are becoming more common on US highways. Thus, the assignment of highway costs responsibilities based on the pavement damage attributable to OW vehicles' pass is a significant task that needs to be addressed.

One of the first steps in distributing pavement damage to highway users is the determination and analysis of pavement damage from the different vehicles classes, including those that are considered OW and SHL. Multiple research studies have assessed damage associated to heavy vehicles. These studies used empirical, ME and Finite Elements (FE) methodologies to evaluate pavement damage from axle and vehicle loads. Despite the different methods, the estimation of damage associated to heavy loads requires the use of an allocator factor that has been commonly represented by Load Equivalent Factors (LEF). LEF is defined as the damage per pass to a pavement by the axle in question relative to the damage per pass of a standard axle load. The concept behind LEFs is the conversion of any axle load and configuration to an equivalent standard axle configuration (18,000 lb single axle) for use in pavement design. Table 2.2 lists research studies on the assessment of pavement damage due to OW vehicles.

Several researchers have applied the LEF concept to investigate the impact of heavy vehicles on pavement. For instance, Sebaaly et al. evaluated the impact of agricultural vehicles on AC pavement rutting for low volume roads using LEFs.(15) The authors determined the ratio of the number of repetitions to failure for an 18,000 lb single axle to the number of repetitions to failure for a given agricultural vehicle axle configuration relative to a surface rutting threshold.

Titi et al. investigated pavement deterioration caused by heavy vehicles in Wisconsin.(16) An OW permit database with over 95,000 entries was used to conduct a routing analysis to identify highway segments that received significant OW traffic. Visual condition surveys were also performed to determine related pavement condition on the identified segments. A strong correlation between OW traffic level and observed pavement distress was found. In another recent study, the impact of OW traffic on pavement life was investigated.(17) Predicted pavement life of different pavement structures was investigated using various OW traffic scenarios. A 1% increase in OW vehicle traffic led to a 1.8% reduction in pavement life was reported.

Researchers have also examined the effect of environmental conditions on pavement performance. In particular, pavement mechanical responses are significantly affected by pavement temperature. Sebaaly et al. concluded that rutting-based LEFs were not constant from season to season due to temperature variation.(15) In another study, the effect of environmental conditions on pavement damage induced by OW bus rapid transit (BRT) was investigated in Nevada.(18) The LEFs for several BRT vehicles were determined using pavement temperature distributions representing different seasons of the year. It was found that pavement damage from BRT vehicles in Nevada is significantly influenced by the variability in passenger ridership and more importantly the corresponding climatic conditions at the time of the trips.

Banerjee and Prozzi documented a framework to determine load equivalencies for individual axle configurations using a ME approach.(19) The concept of LEF was extended to incorporate multiple distresses and to account for vehicle dynamic loading. It was concluded that LEF was significantly affected by axle configuration and the distribution of loads on an axle. Because the LEF method has been used as a measure of OW vehicle damage potential to the pavement, it is essential to understand how different factors influence the LEF. This understanding will be helpful to modify axle configuration and load distribution so that potential pavement damage can be minimized.

Table 2.2. List of Studies on the Assessment of Pavement Damage Due to OW Vehicles.

Study	Author(s)	Publication Year
The Assessment of Damage to Texas Highways due to Oversize and Overweight Loads Considering Climatic Factors [20]	Wu, D., et al.	2017
Assessment of Pavement Damage from Bus Rapid Transit: Case Study for Nevada[18]	Hajj, E. Y., et al.	2016
Practical Approach for Determining Permit Fees for Overweight Trucks[19]	Banerjee, A., and Prozzi, J. A.	2015
Quantification of Accelerated Pavement Serviceability Reduction Due to Overweight Truck Traffic[21]	Dey, K., et al.	2015
Analysis of Data on Heavier Truck Weights Case Study of Logging Trucks[22]	Owusu-Ababio, S., and Schmitt, R.	2015
Pavement-Dependent Load Limits, Case Study in South Dakota for Different Tire Configurations[23]	Wang, H., et al.	2014
Impact of Overweight Traffic on Pavement Using Weight-In-Motion Data and Mechanistic-Empirical Pavement Analysis[17]	Wang, H., et al.	2014
Characterization of Overweight Permitted Truck Routes and Loads in Wisconsin[16]	Titi, H., et al.	2014
Framework for Determining Load Equivalencies with DARWin-ME[24]	Barnerjee, A., et al.	2013
Rate of Deterioration of Bridges and Pavement as Affected by Trucks[25]	Chowdhury, M., et al.	2013
Field Measurement of Pavement Responses Under Super Heavy Load[26]	Dong, Q., and Huang, B.	2013
Evaluating the Effect of Natural Gas Development on Highways, Texas Case Study[27]	Barnerjee, A., et. al.	2012
Impact of Permitted Trucking on Ohio's Transportation System and Economy[28]	Ohio Department of Transportation	2009
Pavement Damage Due to Different Tire and Loading Configurations on Secondary Roads[29]	Al-Qadi, I., et al.	2009
Determination Analysis of Flexible Pavements under Overweight Vehicles[30]	Sadeghi, J. M., and Fathali, M.	2006
Determination of Equivalent Axle Load Factor of Trailer with Multiple Axle on Flexible Pavement Structures[31]	Tjan, A., and Fung, C.	2005
Impact of Busses on Highway Infrastructure, Case Study for New Jersey State[32]	Boile M., et al.	2003
Methodology to Assess Impacts of Alternative Truck Configurations on Flexible Highway Pavement Systems[33]	Suleiman, N., and Varma, A.	2002
Impact of Heavy Vehicles on Low-Volume Roads[15]	Sebaaly, P. E., et al.	2000
Local Urban Transit Bus Impact on Pavements[34]	Gibby, R., and Sebaaly, P. E.	1996

In summary, multiple studies have investigated the impact of OW vehicles on flexible pavement structures. The associated pavement damage can then be used to determine the costs attributable to OW vehicle moves.

Pavement damage associated costs from OW vehicles have also been documented by several studies. Table 2.3 presents a summary of different studies that have examined PDAC from OW vehicles.

Table 2.3. List of Studies on Pavement Damage Associated Costs Attributable to OW Vehicles.

Study	Author(s)	Publication Year
Infrastructure damage-cost-recovery fee for overweight trucks: Tradeoff analysis framework [36]	Dey, K., et al.	2015
Estimation of Pavement and Bridge Damage Costs Caused by Overweight Trucks [35]	Dey, K., et al.	2014
Use of Finite Element Analysis and Fatigue Failure Model to Estimate Costs of Pavement Damage Caused by Heavy Vehicles[39]	Dong, Q., et al.	2014
Potential Impacts of Longer and Heavier Vehicles on Texas Pavements[40]	Weissmann, A., et al.	2013
Oversize/Overweight Vehicle Permit Fee[41]	Prozzi, J., et al.	2012
Allocation of Pavement Damage Due to Trucks Using a Marginal Cost Method[42]	Hajek, J., et al.	2011
Evaluation of Superheavy Load Movement on Flexible Pavements[38]	Chen, X., et al.	2011
Development of Annual Permit Procedure for Overweight Trucks on Indiana Highways[43]	Moffett, D., et al.	2011
Estimating Highway Pavement Damage Costs Attributed to Truck Traffic[44]	Bai, Y.	2010
Process to Estimate Permits Costs for Movement of Heavy Trucks on Flexible Pavements[45]	Tirado, C., et al.	2010
A Synthesis of Overweight Truck Permitting[37]	Bilal, M. K., et al.	2010
A new Approach for Allocating Highway Costs[46]	Hong, F., et al.	2007
Correlation Between Truck Weight, Highway Infrastructure Damage Cost[47]	Timm, D., et al.	2007
Estimating the Costs of Overweight Vehicle Travel on Arizona[48]	Straus, S. H., and Semmens, J.	2006
Infrastructure Costs Attributable to Commercial Vehicles[49]	Boile, M., et al.	2001
Cost of Pavement Damage Due to Heavier Loads on Louisiana Highways[50]	Roberts, F., and Djakfar, L.	2000
Allocation of Pavement Damage Due to Trucks Using a Marginal Cost Method[51]	Hajek, J. J., et al.	1998

A South Carolina study revealed that pavement damage significantly increased when trucks operated above the state legal truck weight limits.(35) PDAC values were estimated to assess the necessary permit fees needed to pay for the pavement damage imparted by OW vehicles. The original study suggested damage cost recovery fee schemes as a function of GVW and VMT in a single-trip. A follow-up study presented a multi-objective analysis approach for determining pavement damage.(36) A trade-off analysis was implemented considering the conflicting goals of minimizing pavement and bridge damage, as well as minimizing permit fees.

In 2010, Bilal et al. presented a synthesis of the truck permitting practice in Indiana and its neighboring states.(37) A comparison among several Midwestern states in terms of permit fee criteria, structure, and amounts across the area was presented. Information from past studies on damage and costs associated to OW loads along with information on the generated revenue and other implications of over-dimensional permitting in the State of Indiana were presented.

In a case study, Chen, X. et al. presented a cost allocation procedure based on the predicted damage attributed to a SHL vehicle move while considering the estimated costs of repairing the deteriorated pavement.(38) The damage caused by a single pass of the SHL movement was compared to that of a standard load by determining an equivalency factor that could be used as a multiplicative factor of repair costs. The equivalency factor is the key for the determination of cost responsibility in this case. In addition, the authors conducted a pavement structural analysis to assess the potential damage of a rapid load-induced shear failure.

In summary Table 2.3 provides a list of multiple research studies whose focus was the estimation of pavement damage costs related to overweight vehicles. It should be noted that the focus of most studies has been on the assessment of pavement damage from a single overweight trip. As a result, the pavement damage and associated costs due to a multi-trip OW vehicle have not been addressed.

2.3 Employed Methodology for Pavement Damage Associated Costs

The goal of this section is to present a mechanistic-based cost allocation approach which will allow for the determination of the pavement damage associated costs attributable to single and multi OW trips in Nevada. The approach suggested by Tirado et al. which implement the highway *cost-occasioned* method to estimate pavement damage associated costs using ME analysis was adopted in this project.(45) This cost allocation approach estimates pavement damage costs based on vehicle axle loading and configuration and considers the predicted pavement life reduction due to a single pass of the evaluated OW vehicle. With this method, different pavement distress models, pavement repair options and any axle configurations can be implemented. The present worth value of repairing costs (PWV) and VMT are also needed inputs of the process.(45) The approach as presented by Tirado et al., was revised in this study to consider the current condition of the pavement at the time of the pass. Consequently, lower PDACs will be estimated for an OW pass occurring on a pavement section with lower remaining life (i.e., a pavement section that has already been subjected to a percentage of its original design traffic). It should be noted that the same methodology was adopted to estimate PDAC for multi-trip permits.

To estimate PDAC, the distress performance models are needed to predict pavement performance and estimate pavement damage under both, OW and reference vehicles. Pavement damage or performance for both OW and reference vehicles are formed and are the basis of associated costs assessment for heavy vehicle passes. A typical 80,000 lb 18-wheel truck with one steering axle (12,000 lb) and two tandem axles (34,000 lb each) was considered as the reference vehicle in this study.

2.3.1. Pavement Performance Prediction Models

Pavement damage predictions are an essential element of this approach. Any realistic damage predictions need to rely on proper locally calibrated distress performance models to appropriately estimate pavement damage under both OW and reference vehicles.(18) Critical pavement responses, as required by the corresponding performance models, need to be determined for each of the axle groups associated with the evaluated OW and reference vehicles.

The Nevada calibrated performance models are employed to estimate pavement damage associated with each axle group. The number of axle-group repetitions to specific rehabilitation failure criteria are estimated using the appropriate equations. For instance, the AC rutting and AC bottom-up fatigue cracking model equations shown in Equation 1 and Equation 2, are implemented as part of this project. It should be noted that these equations are implemented in the Mechanistic-Empirical Pavement Design Guide (MEPDG) and the associated AASHTOWare® Pavement ME software.(14113)

$$\frac{\varepsilon_p}{\varepsilon_r} = 10^{\beta_{r1}k_{r1}}T^{\beta_{r2}k_{r2}}{N_r}^{\beta_{r3}k_{r3}} \qquad [1]$$

Here, ε_p corresponds to the plastic strain, ε_r represents the resilient strain at the mid-depth of the AC layer, *T* corresponds to the AC layer temperature, and N_r represents the number of axle group load repetitions. In addition, k_{r1}, k_{r2}, k_{r3} are global field calibration parameters, and β_{r1}, β_{r2}, β_{r3} are local or mixture field calibration constants.

$$N_f = \beta_{f1}k_{f1}\left(\frac{1}{\varepsilon_t}\right)^{\beta_{f2}k_{f2}}\left(\frac{1}{E_{AC}}\right)^{\beta_{f3}k_{f3}} \qquad [2]$$

Here, N_f is the allowable number of axle group load applications, ε_t is the critical tensile strain at the bottom of the AC layer, and E_{AC} is the dynamic modulus of the AC layer. In addition, k_{f1}, k_{f2}, k_{f3} are global field calibration parameters, and β_{f1}, β_{f2}, β_{f3} are local or mixture field calibration constants.

Table 2.4 presents all three NDOT districts calibration factors for AC permanent deformation and AC bottom-up fatigue cracking performance models.(52) More information on these calibration factors can be found in the *Manual for Designing Flexible Pavements in Nevada Using AASHTOWare Pavement-ME Design*.(52)

Table 2.4. Locally Calibrated AC Performance Model Parameters.

NDOT Districts	**AC Permanent Deformation Performance Model Parameters**					
	k_{r1}	k_{r2}	k_{r3}	β_{r1}	β_{r2}	β_{r3}
I	-2.9708	1.7435	0.3547	0.10451	1.0	1.0
II	-3.2605	2.0055	0.3161	0.16981	1.0	0.9
III	-3.4717	2.0258	0.3946	0.13654	0.9	0.8
	AC Bottom-up Fatigue Cracking Performance Model Parameters					
	k_{f1}	k_{f2}	k_{f3}	β_{f1}	β_{f2}	β_{f3}
I	214.18	5.0284	2.3072	0.005	1.0	1.0
II	30.08	5.0537	2.8904	50	1.0	1.0
III	30.08	5.0537	2.8904	50	1.0	1.0

The allowable number of repetitions for a given vehicle was estimated using Miner's rule as shown below in equation 3.[53]

$$\frac{1}{N_{failure}} = \frac{1}{N_{1:failure}} + \frac{1}{N_{2:failure}} + \frac{1}{N_{3:failure}} + \cdots + \frac{1}{N_{i:failure}} \quad [3]$$

Here, $N_{failure}$ is the estimated number of OW vehicle or reference vehicle passes to the threshold failure; $N_{i:failure}$ are the estimated number of passes to the same threshold failure for the individual axle groups within the OW vehicle or reference vehicle.

In mechanistic analysis of flexible pavements, each set of axle combinations (i.e., single, tandem, or tridem axles) is treated as one single axle group.[14] Subsequently, for each axle group, the maximum pavement response is determined and used for pavement performance prediction. In fact, the performance models are calibrated based on the estimated maximum response (i.e., single response value) for each axle group. In such an undertaking, only a single maximum pavement response for the axle group is required for pavement distress predictions.[14]

The same principle is applicable to OW vehicles which typically have non-standard axle and tire configurations. Thus, the closely spaced axles (say, spacing less than or equal to 72 inch) with identical properties (i.e., similar axle loading, axle spacing, and tire configuration) are combined into a number of single axle groups. Therefore, only the peak response (e.g., maximum tensile strain at the bottom of the AC layer) for each axle group is used with the associated pavement performance model for distress prediction.

Previous studies revealed that when the spacing between two adjacent axles are more than 60 inch, the pavement responses under one of the axles do not get influenced by the adjacent axle load (i.e., no or minimal interaction among the two adjacent axles).[53] Such criteria for axle spacing can be employed to define the various axle groups for an OW vehicle. Accordingly, two or more axles with identical properties and axle spacing less than 60 inch can be classified as they belong to a single group of axles. It should be mentioned that the selected limit of 60 inch is consistent with the routinely used assumption to consider tire groups present on only one side of the standard truck.

For instance, Figure 2.1 shows a schematic of the axles' configuration for a given OW vehicle. Using the 60-inch criterion for axle spacing, the OW can be divided into seven axle groups; a steering single axle (A group), a tridem axle (B group), and five tandem axles (C, D, E, F, and G groups). As an example, Figure 2.2 to Figure 2.4 show the tensile strain history response at the bottom of the AC layer determined using the 3D-Move Analysis software for the defined axle groups.[54] The OW vehicle was assumed to travel over a flexible pavement structure that consisted of a 6 inch of AC over 10 inch of Crush Aggregate Base (CAB) over a subgrade (SG). The responses are shown for a vehicle travel speed of 45 mph and an AC layer temperature of 70°F.

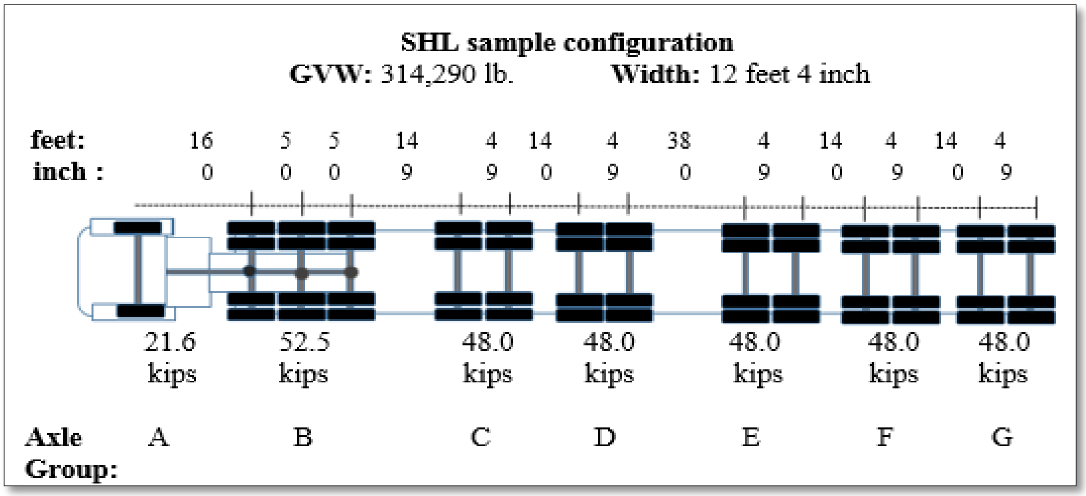


Figure 2.1. Example for an OW vehicle configuration.

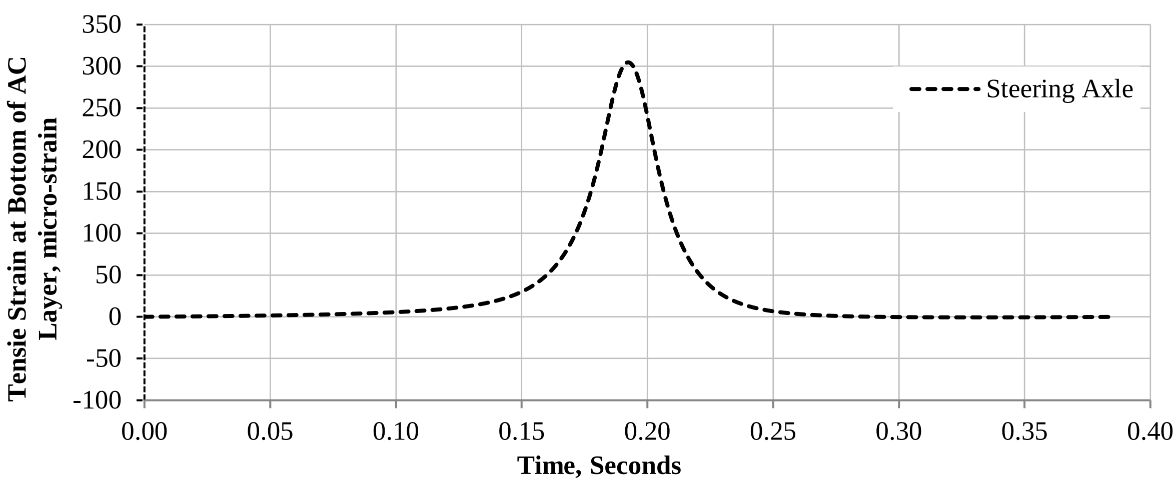


Figure 2.2. Tensile strain response history at the bottom of AC layer for axle group A (single axle).

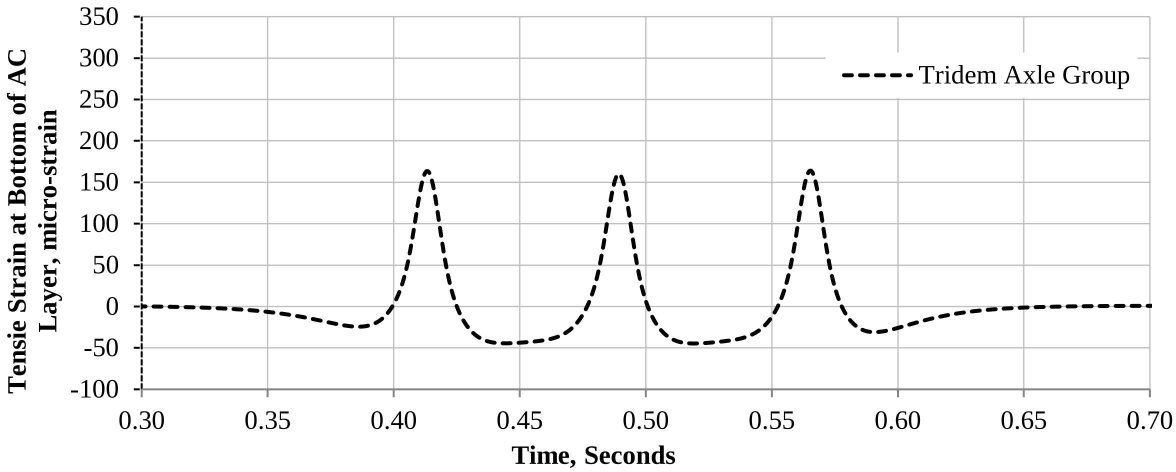


Figure 2.3. Graph. Tensile strain response history at the bottom of AC layer for axle group B (tridem axle).

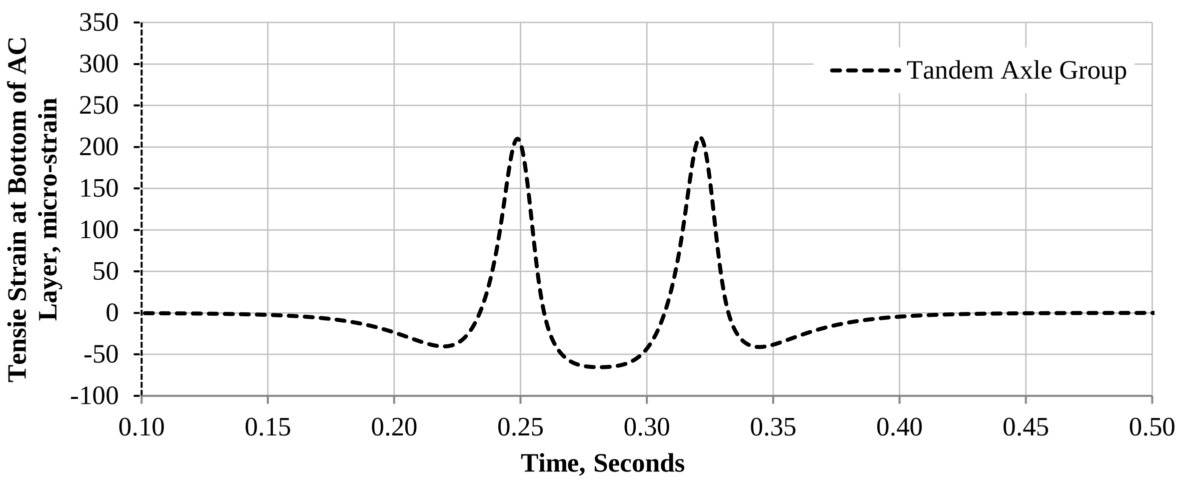


Figure 2.4. Graph. Tensile strain response history at the bottom of AC layer for axle groups C, D, E, F, and G (tandem axle).

In the case of tridem axle shown in Figure 2.4, three distinct peaks for the tensile strain response are observed (one peak strain under each of the three axles within the tridem axle). Although the peak values for the tensile strain are similar, the tridem axle is counted as one pass and the allowable number of load repetitions to fatigue failure is calculated using the maximum strain value induced by the entire tridem axle group. Note that the same assumption is used during the calibration process of the performance models and distress transfer functions in the MEPDG. It should be noted that if all the peak strains in a response history are individually considered for distress prediction, the analysis would severely underestimate the pavement performance under the OW vehicle. Thus, resulting in improper (higher) estimates for pavement damage and associated costs.

2.3.2. Load Equivalency Factors

As noted earlier, the load equivalent factor (LEF) is a key parameter in pavement design and analysis. Estimation of pavement damage has historically been related to LEFs. The LEF concept was an outcome of the AASHO road test in 1960's.[55] The concept behind LEFs is the conversion of any axle load and configuration to an equivalent standard or reference axle configuration (18,000 lb single axle) for use in pavement design. As mentioned before, several studies have applied this concept to investigate the impact of heavy vehicles on pavement damage. In this research effort, the concept of LEF was expanded to develop mechanistic empirical LEF corresponding to AC rutting and fatigue cracking for each and every axle of OW and reference vehicles using the following relationship.

$$LEF = \frac{N_{18}}{N_{axle}} \tag{4}$$

Here, N_{18} and N_{axle} represent the number of repetitions to AC rutting or fatigue cracking failure corresponding to the reference axle and specific OW vehicle axles, respectively. The LEF for an entire OW vehicle was determined by summing the LEFs of its individual axles.

2.3.3. Pavement Damage Associated Costs Methodology Steps

To estimate PDAC, distress performance models are needed to predict pavement performance and estimate pavement damage under both, OW and reference vehicles. The estimated damage is then used to calculate the PDAC due to a single pass of the OW vehicle. The overall flowchart for the cost allocation analysis method is presented in Figure 2.5, and it can be summarized in the following eleven steps.[45]

- *Step 1.* Damage curves based on a specific performance model prediction model and to a specific threshold are first developed for OW and reference vehicles to relate predicted distress to vehicle passes.
- *Step 2.* The number of reference vehicle passes to reach the established failure threshold is determined as $N_{std:f}$.
- *Step 3.* The amount of distress after a specific number of passes (e.g., 10,000 passes) of the reference vehicle is estimated from the reference vehicle damage curve and named as $d_{\mathrm{Nstd:10,000}}$.
- *Step 4.* The number of OW vehicle passes to cause the same amount of distress as $d_{\mathrm{Nstd:10,000}}$ is determined from the OW vehicle damage curve and defined as $N_{truck:eq}$.
- *Step 5.* The damage caused by an extra pass of the OW vehicle after $N_{truck:eq}$ is determined from the OW vehicle damage curve and called $d_{truck:eq+1}$.
- *Step 6.* The number of additional passes of the equivalent reference vehicle to cause $d_{truck:eq+1}$ is estimated from the reference vehicle damage curve and called $\Delta N_{std:eq}$.
- *Step 7.* The percentage of pavement life reduction (LR) is obtained from one pass of the OW vehicle and calculated as shown below.[45]

$$LR = \frac{\Delta N_{std:eq}}{N_{std:f}} \tag{5}$$

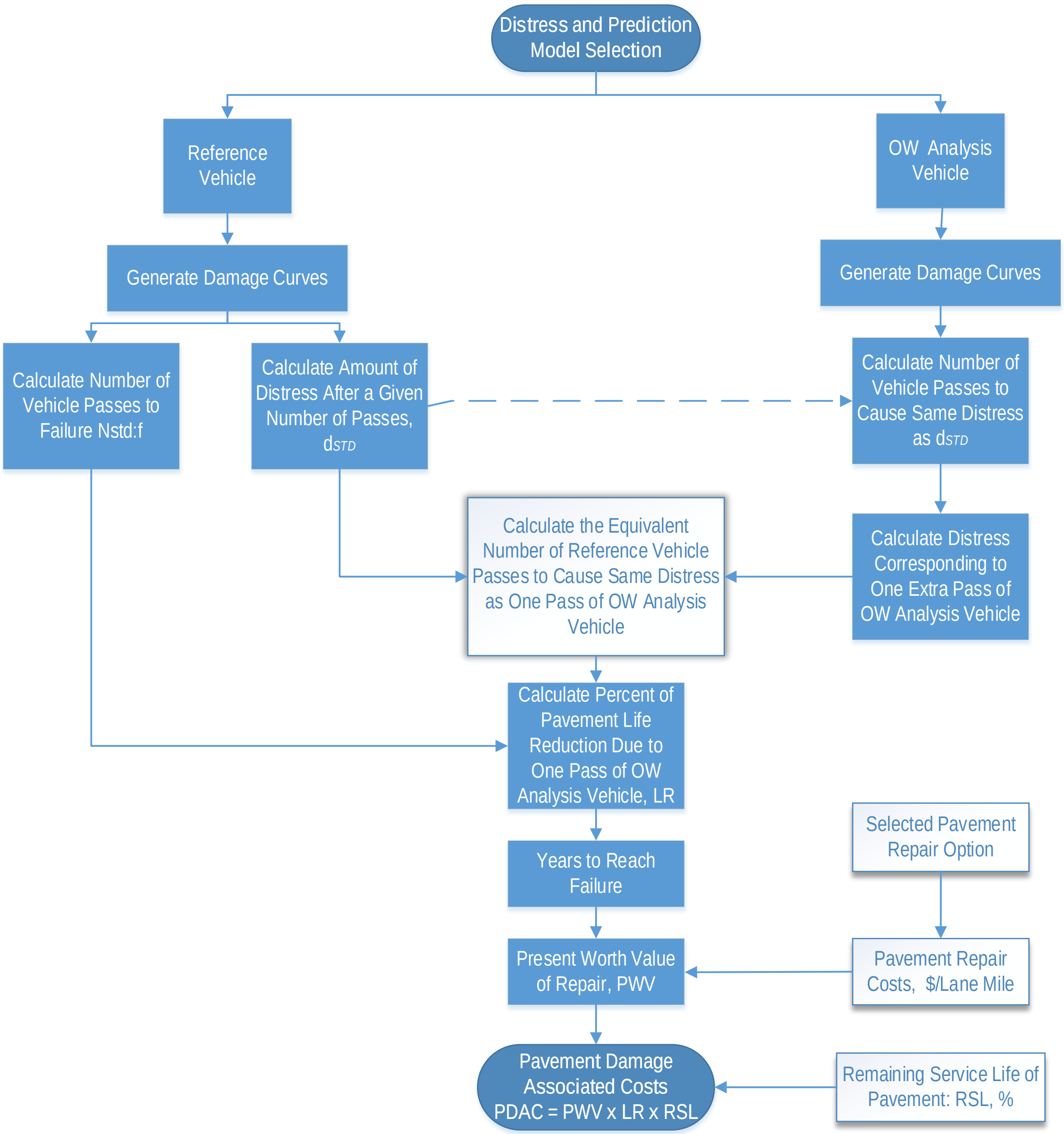


Figure 2.5. Flowchart of overall approach for the estimation of pavement damage and allocated cost.

- *Step 8.* The pavement service life in years, *n*, is determined as a function of the actual annual average daily traffic, annual average daily truck traffic (AADTT), and $N_{std:f}$ as following.[45]

$$n = \frac{N_{std:f}}{AADTT \times 365} \quad [6]$$

- *Step 9.* The present worth value, PWV, of repairing the pavement when the failure threshold is reached is calculated as shown below.[45]

$$PWV = \frac{Cost}{(1+Discount\ Rate)^n} \quad [7]$$

- *Step 10.* To consider the remaining service life of the pavement at the time of the OW move, the remaining service life factor, *RSL*, was introduced and is calculated following the equation shown below. Here, the *Year of OW Pass* is defined as the year when the OW movement is expected to take place. The *Year of Last Repair* is the year when the last structural pavement repair took place. Finally, the *Year of Next Repair* is defined as the year of the next scheduled structural pavement repair.

$$RSL = 1 - \frac{Year\ of\ OW\ \ Pass - Year\ of\ Last\ Repair}{Year\ of\ Next\ Repair - \ Year\ of\ Last\ repair} \quad [8]$$

- *Step 11.* The PDAC is calculated based on the product of PWV, LR, and RSL as shown below:

$$PDAC = PWV \times LR \times RSL \quad [9]$$

2.3.4. Inputs Needed for Costs Allocation Analysis

As presented in previous sections, multiple variables are needed to determine PDAC using the proposed methodology. These values can be classified as general inputs and inputs specifically related to the existing pavement layers. Table 2.5 presents a complete summary of all necessary inputs for conducting the cost allocation analysis.

General inputs are values required in the determination of PDAC regardless of the pavement performance model used. The discount rate is a critical component in the PVW calculation. A value of 2 to 4% is usually used. The number of repetitions of the reference vehicle prior to the pass of the analysis vehicle is an estimate needed in the PDAC calculation algorithm. The AADTT is an important value needed to estimate the number of years to failure due to passes of reference vehicle. The Pavement repair activity costs are converted to PWV over the number of years needed to reach failure. NDOT rehabilitation repair costs for different NDOT road categories were implemented as part of this study. However, this value can be selected by NDOT depending on the type of structural repair activity planned for the pavement section. Table 2.6 presents typical rehabilitation repair costs for different NDOT road categories.[52]

Table 2.5. Summary of Input Variables needed for Estimation of Pavement Damage and PDAC

Input	Description	Unit
General	Discount rate	Percent
	Number of repetitions of reference vehicle prior to the pass of analysis vehicle	Positive real number
	AADTT	Positive real number
	Repair activity costs	US Dollars/lane-mile
AC Layer	Maximum vertical strains at the middle of AC layer for reference and analysis vehicles' axles	inch/inch
	AC Permanent deformation model parameters	Real number
	Allowable permanent deformation in AC layer	Inch
	Maximum tensile strains at bottom of AC layer for reference and analysis vehicles' axles	inch/inch
	Allowable bottom-up fatigue cracking in AC layer	percent
	Bottom-up fatigue cracking performance model parameters	Real number
	Pavement temperature at middle of AC layer	Degrees Fahrenheit

Table 2.6. Rehabilitation Repair Costs for Different NDOT Road Categories.

Road Category	Rehabilitation Activity	Rehabilitation Cost (US Dollars per Lane-Mile)
1	1 inch Mill, 2 inch AC and Open-Graded Wearing Course	267,500
2	1 inch Mill, 2 inch AC and Open-Graded Wearing Course	237,500
3	2 inch AC and Open-Graded Wearing Course	215,000
4	2 inch AC and Open-Graded Wearing Course	200,000
5	2 inch AC and Chip Seal Surface Treatment	160,000

Inputs specifically related to the existing AC layers are also needed in the determination of PDAC. Pavement damage predictions are key elements of the proposed mechanistically based methodology. Thus, critical pavement responses at different locations within the pavement structure are determined for each of the axle groups identified for the OW and reference vehicles. The AC permanent deformation and AC fatigue cracking calibration factors (see Table 2.4) are also critical values in the determination of pavement damage and PDAC. The allowable distress threshold before a structural repair activity is an important factor in the methodology, as this factor directly impact pavement damage and PDAC. Table 2.7 summarizes the design and rehabilitation threshold values for different NDOT road categories as suggested in the *NDOT Manual for Designing Flexible Pavements in Nevada Using AASHTOWare Pavement-ME Design*.[52]

Table 2.7. Design and Rehabilitation Threshold Values for Different NDOT Road Categories.

Road Category	Two Directional ADT and ESALs (Daily)	AC Permanent Deformation Threshold (inch)		AC Bottom-Up Fatigue Cracking Threshold (percent)	
		New	Rehabilitation	New	Rehabilitation
1	Controlled Access Asphalt				
2	ESALs > 540 or ADT > 10,000				
3	405 < ESALs < 540 or 1,600 < ADT 10,000 + NHS	0.15	0.10	15.00	5.00
4	270 < ESALs < 405 or 400 < ADT < 1,600				
5	ADT < 400				

2.4 Illustrative Example

To illustrate the proposed cost allocation methodology, the step-by-step calculations are presented for the PDAC of an OW vehicle with a GVW of 500,825 lb. The OW movement was proposed to happen in southern Nevada with a VMT of 22 miles. Figure 2.6 illustrates the characteristics of the OW vehicle including: axle load and configuration, vehicle width, and number of vehicle miles travel. The costs allocation methodology requires the prediction of pavement damage under both the OW and the designated reference vehicles using the respective critical responses. In this section, the methodology is demonstrated for the case of AC permanent deformation. It should be noted that the width of the OW vehicle is 20 feet and 5 inch which will span over two lanes. Similarly, information about the reference vehicle used in the calculation of the PDAC is also shown in Figure 2.7. The reference vehicle consisted of a 5-axle truck with 18 wheels and a GVW of 80,000 lb.

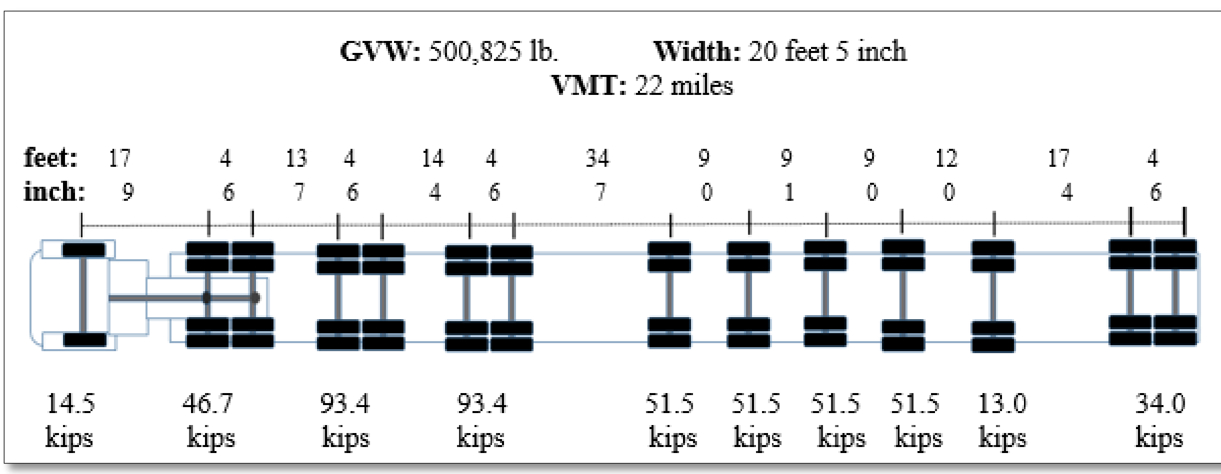


Figure 2.6. OW vehicle configuration.

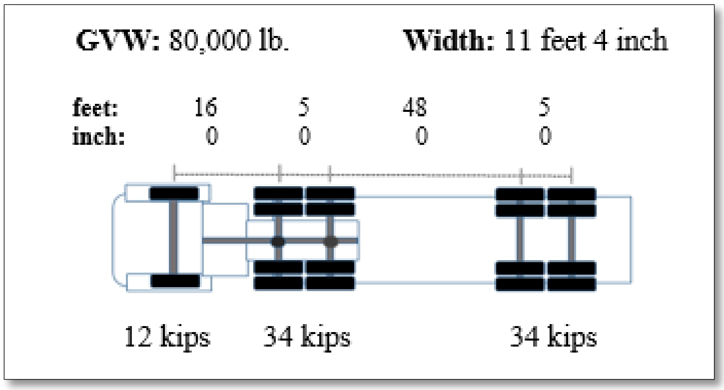


Figure 2.7. Reference vehicle configuration.

The critical pavement responses under the OW and reference vehicles were determined using the 3D-Move Analysis software.(54) In this example, it is assumed that the OW vehicle will travel over a flexible pavement structure consisting of a 6 inch of AC over 10 inch of CAB over the subgrade. The AC layer consisted of a polymer-modified dense-graded asphalt mixture using PG76-22NV asphalt binder. This asphalt mixture is typically used by NDOT in southern Nevada. The measured dynamic modulus of the asphalt mixture was used in this analysis.

Table 2.8 summarizes the maximum vertical strains in the middle of the AC layer under both the OW and reference vehicles. These responses are needed for the estimation of permanent deformation in the AC layer. An operational vehicle speed of 35 mph and an AC analysis temperature of 110°F were used in this example. The high temperature used is considered a representative temperature for the AC layer during the day in the month of June.

Table 2.8. Critical Responses under OW and Reference Vehicles Traveling at 35 mph.

Vehicle Type	Vehicle GVW, lb	Axle Type	Axle Spacing		Number of Wheels	Axle Weight, lb	Maximum Vertical Strain in the Middle of AC at 110°F, microstrain
			feet	inch			
OW	500,825	Steering	NA	NA	2	14,500	354.8
		Tandem	4	6	8	46,725	354.8
		Tandem	4	6	8	93,400	394.7
		Tandem	4	6	8	93,400	394.7
		Single Dual	NA	NA	4	51,450	384.2
		Single Dual	NA	NA	4	51,450	384.2
		Single Dual	NA	NA	4	51,450	384.2
		Single Dual	NA	NA	4	51,450	384.2
		Single Dual	NA	NA	4	13,000	302.6
		Tandem	4	6	8	34,000	333.9
Reference	80,000	Steering	NA	NA	2	12,000	373.6
		Tandem	5	0	8	34,000	333.9
		Tandem	5	0	8	34,000	333.9

Following the cost allocation steps presented in Section 2.3.3, the PDAC for the OW vehicle presented in Figure 2.6 was determined. It should be noted that permanent deformation calibration constants for southern Nevada were implemented in this example for pavement damage estimation.

- *Step 1.* Figure 2.8 presents the damage curves related to AC permanent deformation for both OW and reference vehicles. It can be noted that for a fixed permanent deformation in AC layer, a significantly lower number of passes is expected for the OW vehicle when compared to the reference vehicle.

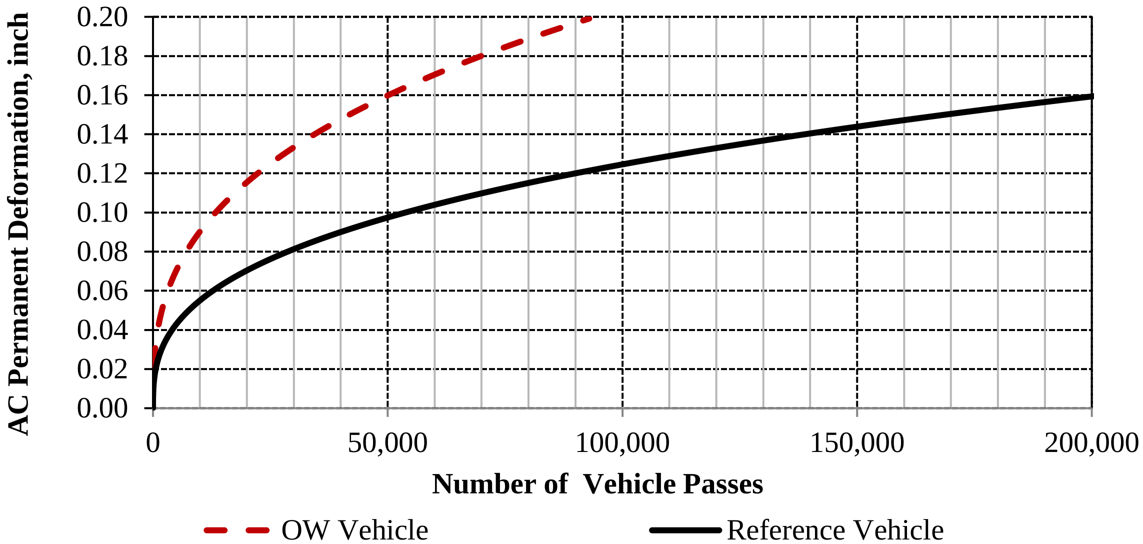


Figure 2.8. AC permanent deformation damage curves under OW and reference vehicles.

- *Step 2.* The number passes of the reference vehicle for a failure criterion of 0.15 inch, $N_{std:f}$, is calculated to be 170,000 passes (Figure 2.9).

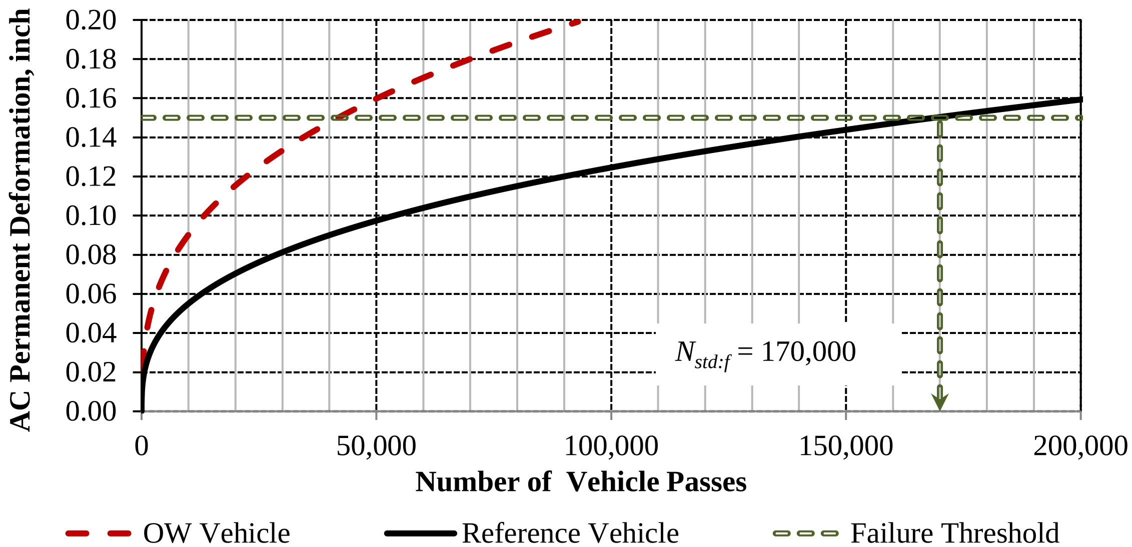


Figure 2.9. Number of reference vehicle passes to failure.

- *Step 3.* The AC permanent deformation after a specific number of passes (in this case 10,000 passes), $d_{\mathrm{Nstd:10,000}}$, is determined to be 0.054 inch as shown in Figure 2.10.

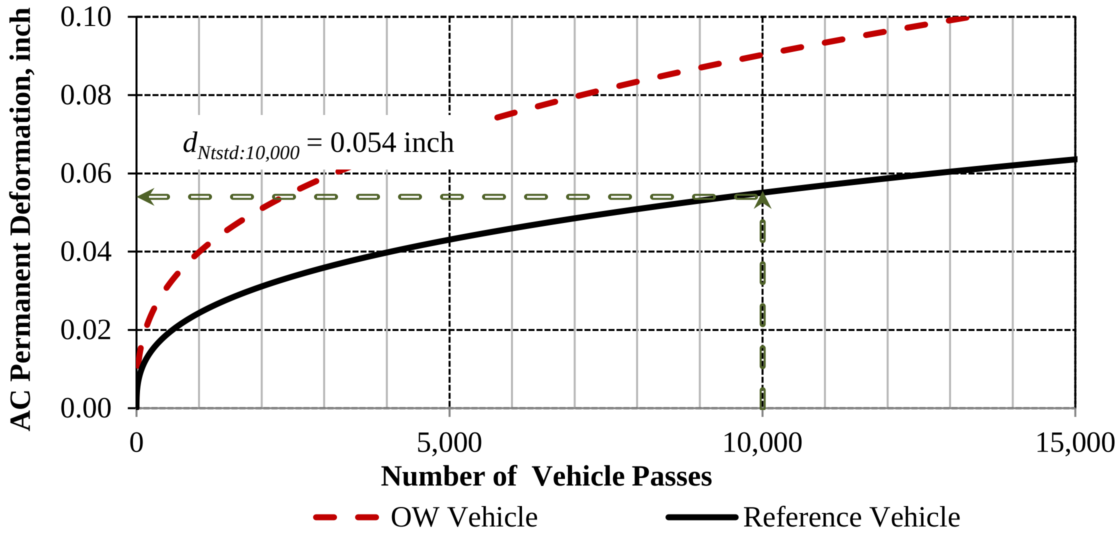


Figure 2.10. AC permanent deformation after 10,000 passes of reference vehicle.

- *Step 4.* The number of OW vehicle passes to cause the same amount of permanent deformation as $d_{Nstd:10,000}$ (0.054 inch), $N_{truck:eq}$, is determined to be 2,350 passes as shown in Figure 2.11.

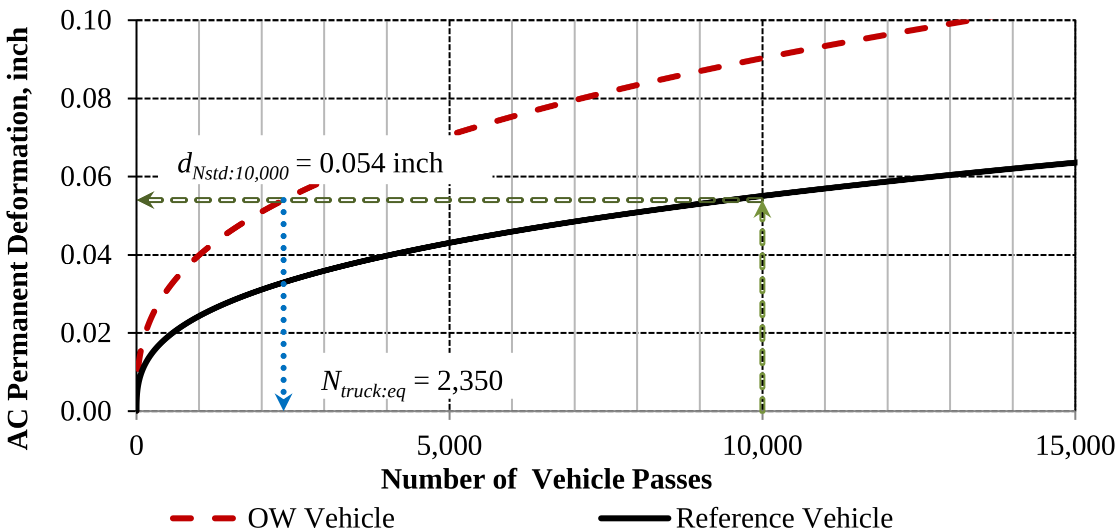


Figure 2.11. Equivalent number of OW vehicle passes after 10,000 passes of the reference vehicle.

- *Step 5.* The damage caused by an extra pass of the OW vehicle after 2,350 passes, $d_{truck:eq+1}$, is determined from the OW vehicle damage curve to be 0.056 inch as shown in Figure 2.12.

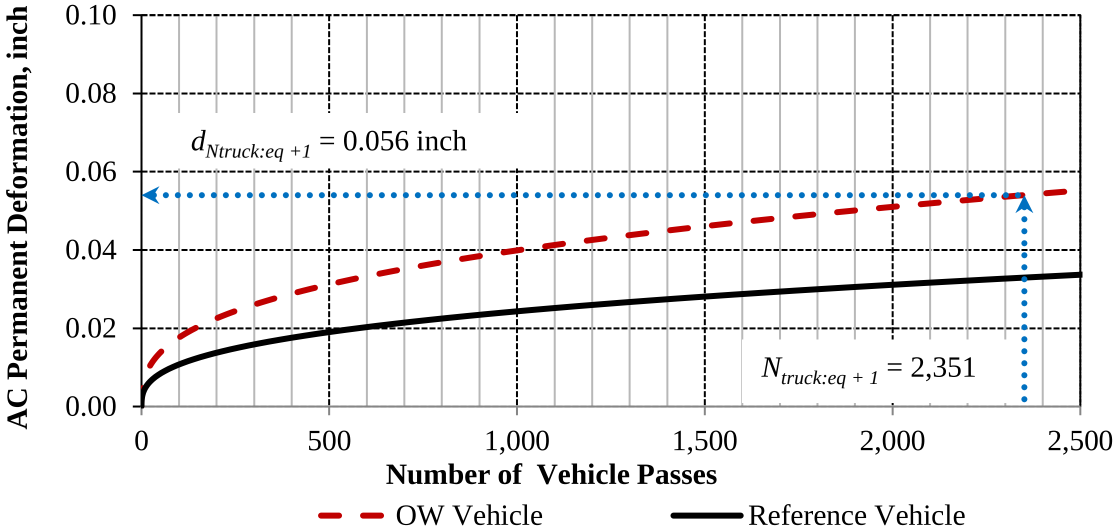


Figure 2.12. AC permanent deformation after $N_{truck:\,eq+1}$.

- *Step 6*. The number of additional passes of the reference vehicle to cause $d_{truck:eq+1}$ (i.e., 0.056 inch) after 10,000 passes of the reference vehicle is determined to be 2.89 as shown in Figure 2.13.

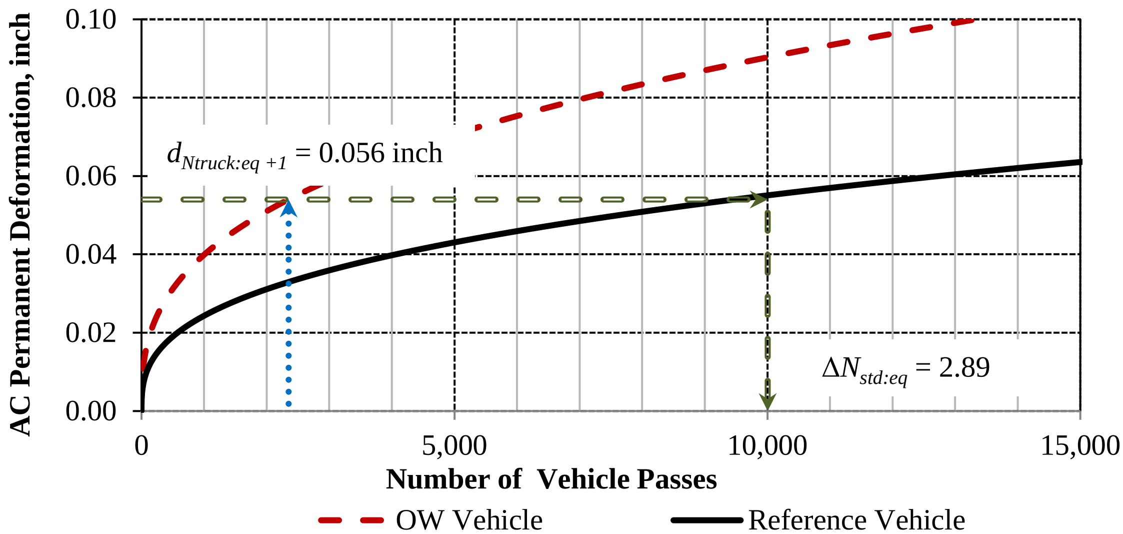


Figure 2.13. Additional number of reference vehicle passes to reach $d_{truck:eq+1}$.

- *Step 7*. The pavement life reduction (*LR*) is then calculated to be 0.000017 as shown below.

$$LR = \frac{2.89}{170{,}000} = 0.000017 \qquad [10]$$

- *Step 8*. The pavement service life in years is determined assuming an AADTT of 100.

$$n = \frac{170{,}000}{100 \times 365} = 4.65\ years \qquad [11]$$

- *Step 9.* The present worth value, PWV, was obtained assuming a pavement repair costs per lane-mile of 350,000 US dollar and a discount rate of 2.0%.

$$PWV = \frac{350{,}000 \text{ US dollar/lane}-\text{mile}}{(1+0.02)^{4.65}} = 319{,}212 \text{ US dollar/lane} - \text{mile} \qquad [12]$$

- *Step 10.* A remaining service life of the pavement section is assumed to be 90 percent.

- *Step 11*. PDAC calculation is shown in US dollar per lane-mile and US dollar per trip, respectively.

PDAC = (319,212) (0.000017) (0.9) = 4.88 US dollar/lane-mile [13]

PDAC = (4.88 US dollar/lane-mile) (22 mile) (2 lanes) = 214.72 US dollar/trip [14]

The total PDAC for the studied OW vehicle move based on AC permanent deformation was about 215 US dollar. It is important to note that the calculated PDAC corresponds to the OW vehicle traveling at a speed of 35 mph and at an estimated temperature in the AC layer of 110°F during the move.

In summary, while several factors might be influencing the analysis, the presented example highlights the proposed procedure to calculate the PDAC due to a single pass of the evaluated OW vehicle on a flexible pavement. In particular, the selection of the pavement distresses of interest along with their associated locally-calibrated performance models become another critical factor in the appropriate determination of the PDAC.

CHAPTER 3 REVIEW OF HISTORICAL OVERWEIGHT VEHICLE PERMITS

One of the main tasks in this investigation was the characterization of typical OW vehicle types, axle groups, axle configurations and axle loads in Nevada. Accordingly, the NDOT OS/OW permit database for ten years of historical data (2004-2013) including 367,595 entries was reviewed and analyzed. Along with this electronic database, NDOT provided thousands of submitted OS/OW permit forms that described GVW and axle/load configurations of permitted vehicles. The database records were classified using different criteria. The purpose of the evaluation of the database and permit forms was the identification of most common ranges of GVW, axle and tire loads and configurations, along with other characteristics of OW vehicles. For instance, some specific types of OW trips were found much more common than others, potentially contributing more to the attributed pavement damage in the state. The information from the database was evaluated and used to categorize permits according to their size, weight, and load type. To perform the different classifications, different criteria were used. The following fields were evaluated in the analysis: GVW, vehicle size, and load description. Other fields included in the database were:

- Permit Type (5-days, i.e., single-trip; or annual/semi-annual, i.e., multi-trip)
- Permit Dates
- Permit Route
- Load Description
- Dimensions
- Requester Company Name
- Amount Paid for Permit
- GVW

It is noteworthy to mention that the OS/OW electronic database did not contain information related to the OW vehicle axle and load configurations. As a result, the additional information found in the permit forms was essential in further characterizing permitted OW vehicles in Nevada.

3.1 Summary of Historical OW Vehicle Permits

First, the permits were classified as either OS only, OW only or OS/OW. Figure 3.1 presents a pie chart showing the database permits classified by type. There was a small percentage (1%) of permits in the database that did not contain dimension information. Thus, the classification of those permits was not possible. It was determined that 42% of permits presented both OS/OW characteristics. Permits identified as OW only accounted for 4%. On the other hand, the percentage of OS only permits was 53%. Furthermore, more than half of the database entries were not classified as OW vehicles. Figure 3.2 presents the proportion of OS/OW permits per year and the number of permits issued during the years of 2004 to 2013.

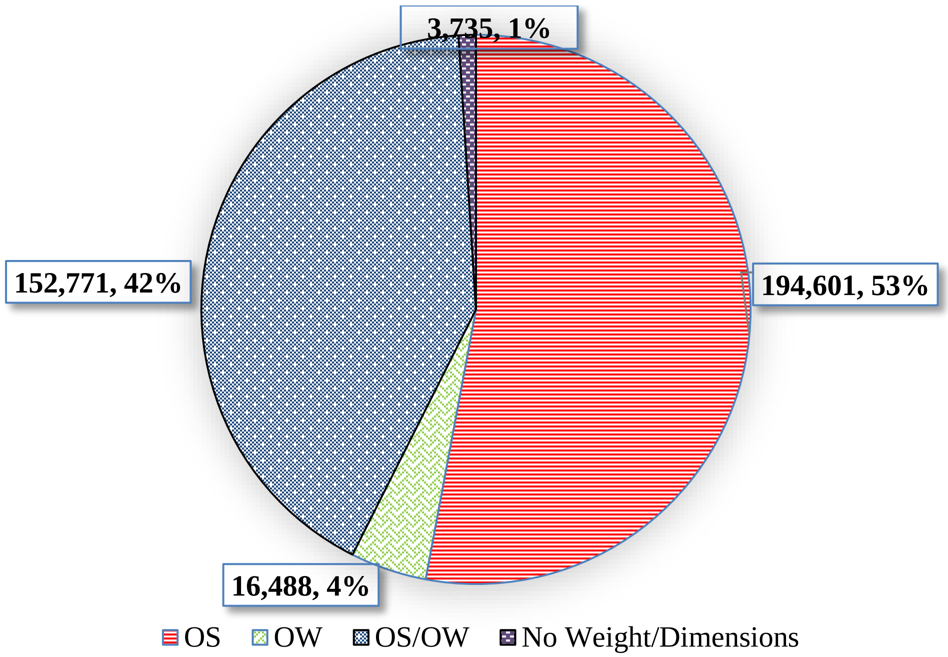


Figure 3.1. Permits classification by type.

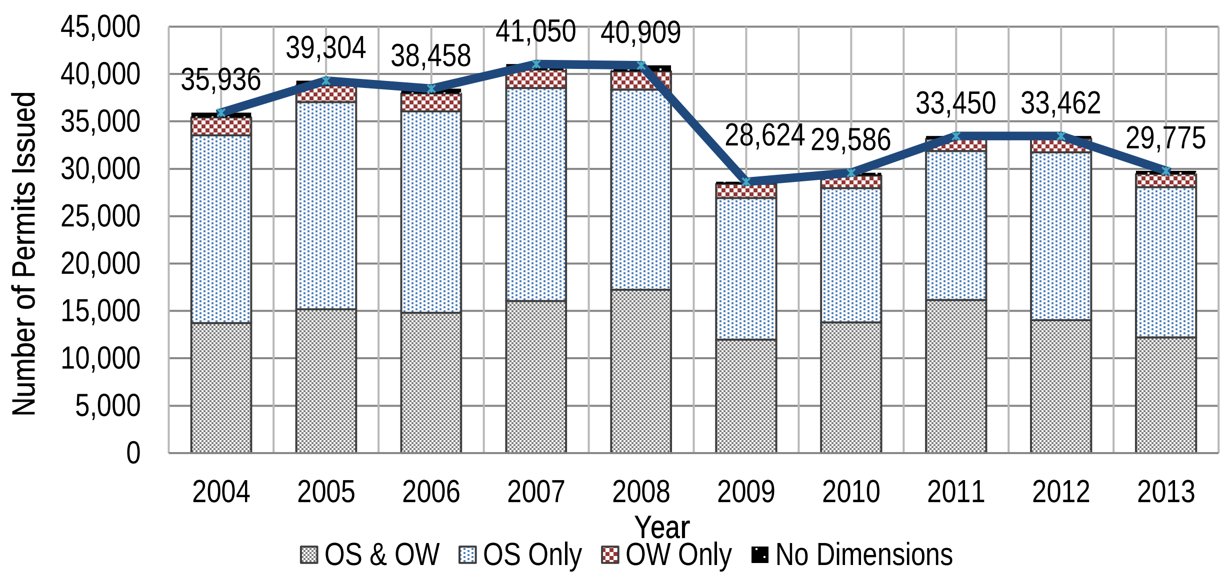


Figure 3.2. Number of permits issued and proportions per year.

As mentioned before, NDOT issues two types of permits. These are multi-trips (annual, semi-annual) and single-trips (5-day). The entries found in the database were classified as single-trip and multi-trip. It was identified that single permits corresponded to 86% of all the permits issued during the evaluated 10-year period. In contrast, annual permits corresponded to 14% of the total permits issued. Hence, multi-trip permits constitute a significant portion of the total permits issued annually. It is challenging to identify with certainty the number of individual trips associated with each multi-trip permit. Additionally, the date and time when the trips take place within the duration of the permit is unknown for the agency. Potentially each multi-trip permit can be associated to multiple single trips. For example, assuming that each annual permit conveys 15 to 20 trips per year, thus the number of OS/OW movements is determined by multiplying the number of annual permits by the assumed number of trips per permit and then added to the total number of single-trip movements. Only then, the total number of OS/OW trips associated with issued permits in Nevada can be estimated. Thus, underscoring the significance of the potential pavement damage and associated costs attributable to multi-trip OW permits which should not be ignored. Figure 3.3 provides a representation of the permit classification by duration of the permit.

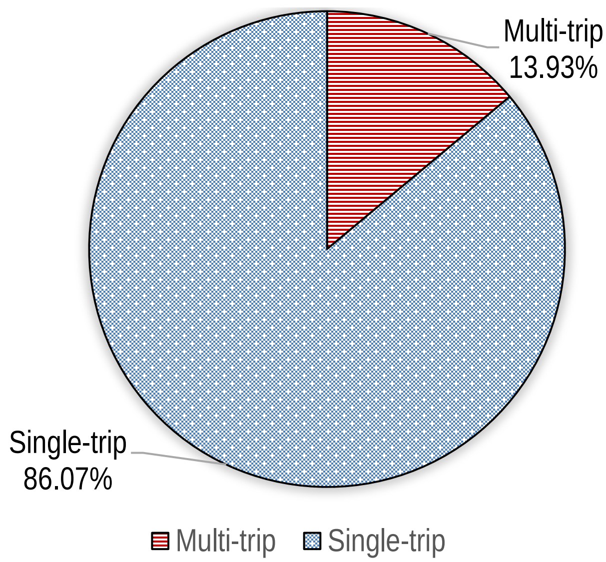


Figure 3.3. Permits classification by duration.

The operation of OW vehicles has become essential to support the operation, expansion, and development of important industries in the nation. In fact, multiple industries rely on the transportation of different commodities using OS/OW vehicles in the state. By scrutinizing the database and analyzing load descriptions of each permit entry, a classification of the most common industries employing OS/OW vehicles was completed. Figure 3.4 presents a pie chart showing the most common industries requesting OS/OW permits in Nevada. Most OW movements are attributed to construction and materials equipment, and to a lesser extent to electrical, mechanical, and mining equipment. A significant amount of OW permits are also attributed to mobile homes and buildings, and to the move of farming and agriculture equipment. The "other" category includes military equipment, buses, planes, boats, etc. representing only 3% of the total number of issued permits

Figure 3.5 presents the construction/materials and the mechanical/electrical equipment categories (most common categories) distributed over several GVW ranges. This figure shows that the most common GVW range of both categories is 80,000 to 150,000 lb. An important number of permits are within the 150,000 to 250,000 lb GVW range. The entries with less than 80,000 lb are OS only vehicles.

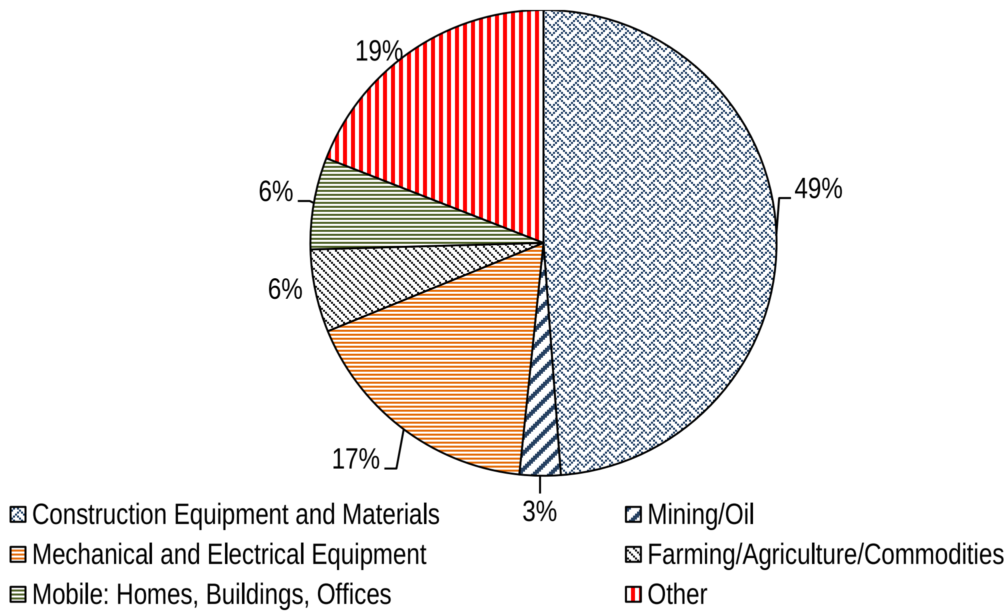


Figure 3.4. Share of industries requesting OS/OW permits in Nevada.

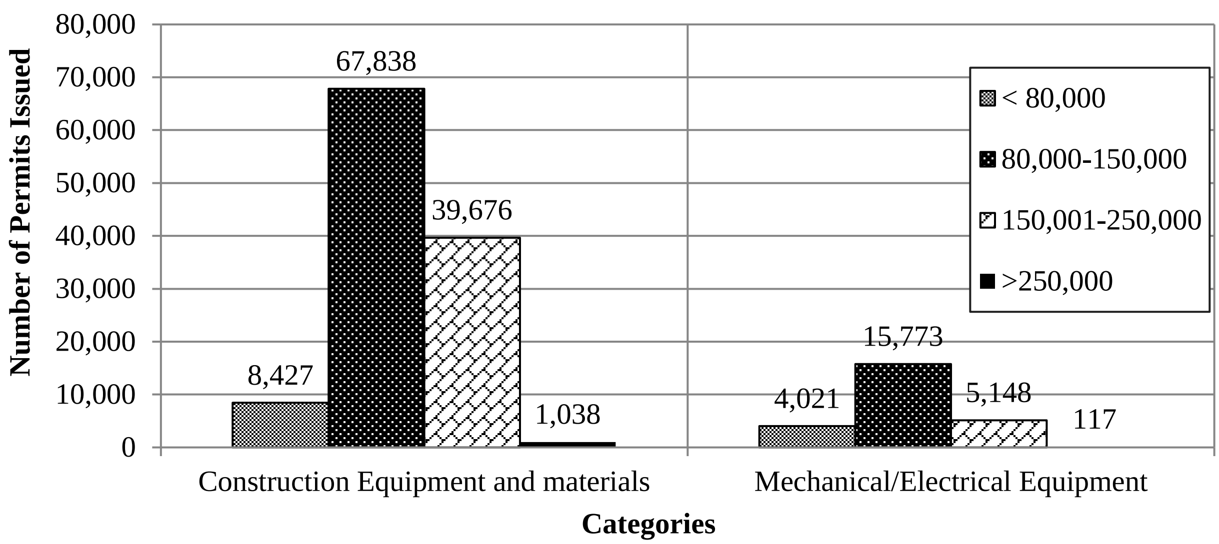


Figure 3.5. Construction and mechanical/electrical issued permits distributed by GVW.

There is a relatively small percentage of vehicles transporting loads with GVW greater than 250,000 lb. Most of these loads corresponded to construction equipment. As noted before, this kind of movements usually require a detailed engineering analysis to determine the structural adequacy and the likely of instantaneous shear failure of the pavement. Such analyses are either performed by the SHA or an independent engineering consulting firm.

The remaining categories were also distributed over the same weight ranges as the construction and electrical equipment categories and are presented in Figure 3.6. Except for the Unladen category (corresponding to the vehicle weight without load), the GVW range with the most permits issued was again 80,000 to 150,000 lb.

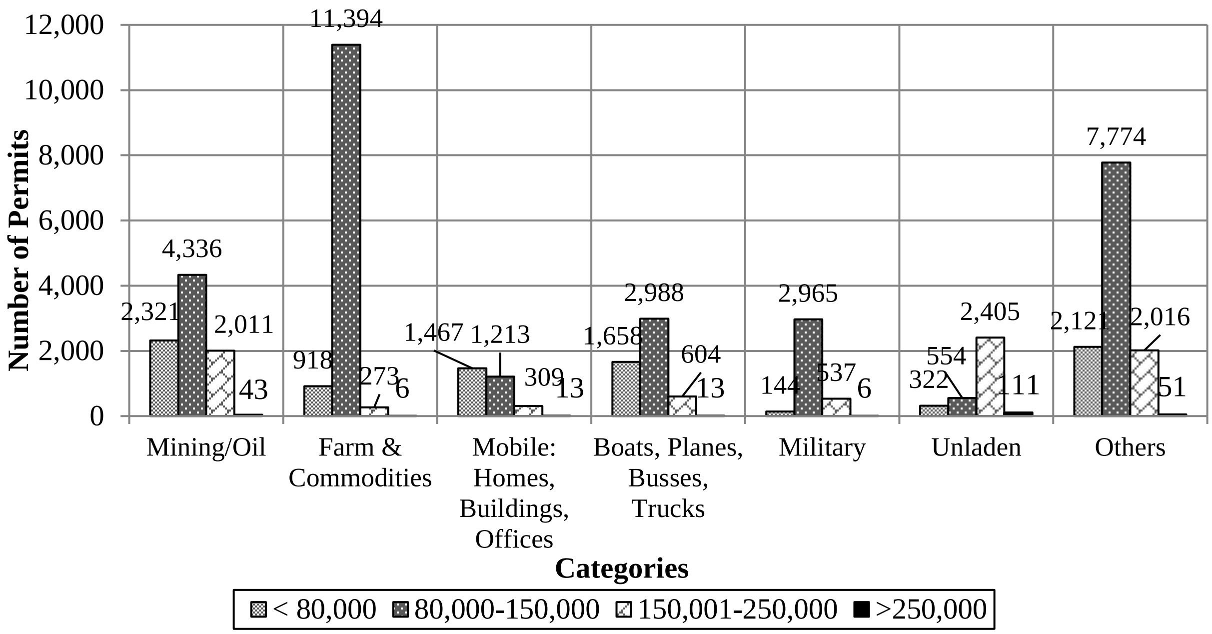


Figure 3.6. Remaining categories of issued permits distributed by GVW.

The total number of SHL vehicles in the database was 1,398 (i.e., OW vehicles with GVW more than 250,000 lb). From this, 89% or 1,245 permits corresponded to vehicles with a GVW less than 500,000 lb. The remaining 11% were distributed over vehicles carrying from 500,000 lb to more than 3,000,000 lb. In the ten-year analysis period more than 100 SHL movements carried loads with more than 1 million lb.

Figure 3.7 summarizes the distribution of SHL vehicles carrying more than 250,000 lb. In this 10-year period, the highest GVW recorded was 6,215,398 lb, corresponding to the construction equipment category. It is important to note that 47 of the issued permits consisted of vehicles carrying more than 3,000,000 lb, which often require specialized trailers and hauling units. A descriptive statistical summary for these SHL vehicles is presented in Table 3.1.

Table 3.1. Summary of GVW for Superheavy Load Vehicles from Issued Permits.

Categories	Number of Permits Issued	Minimum, lb	Maximum, lb	Average, lb	Median, lb
Construction	1,041	250,041	6,215,938	540,631	252,788
Mining and oil	53	250,041	6,112,775	525,728	254,325
Farming	4	294,170	1,572,971	1,135,136	1,336,701
Mechanical and Electrical Equipment	170	250,063	6,123,268	615,711	259,493
Others	130	250,150	2,094,013	348,317	283,170

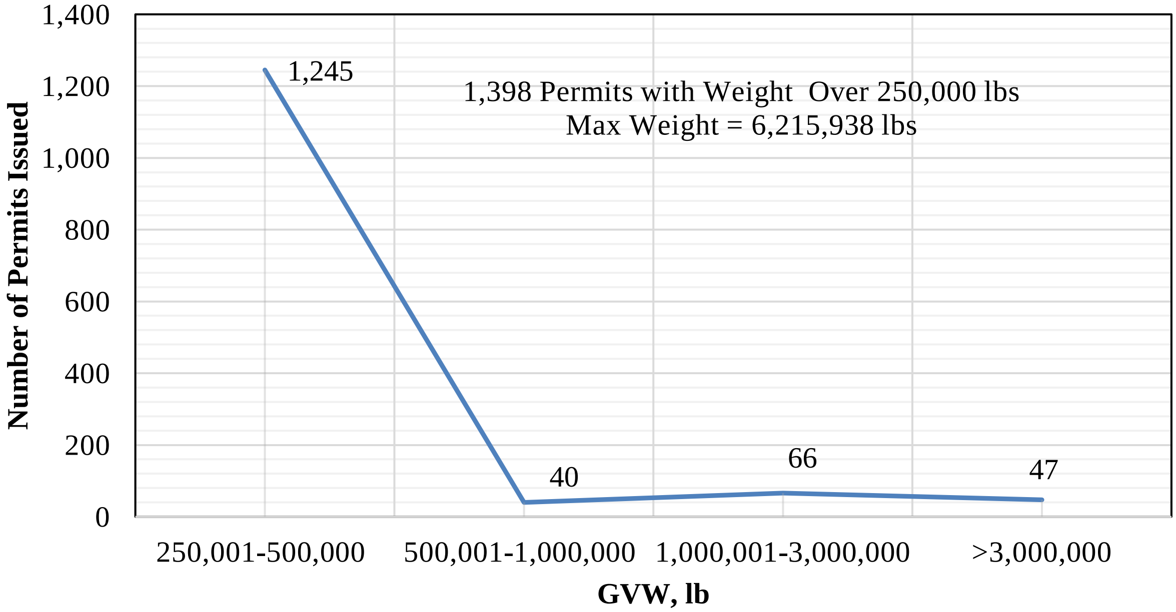


Figure 3.7. Superheavy load vehicle permits issued between year 2004 and 2013.

3.2 Representative Ranges for OW Vehicle's Configurations

Representative distributions of GVW, axle loads, and axle types were obtained by analyzing the 10-year permit database and sample permit forms. It should be mentioned that only vehicles classified as OW were considered. Key information, such as truck configuration, GVW, axle load and number of tires were extracted and used in the analysis. The database entries were inspected for common OW vehicle configurations. For example, more than 10 different truck configurations were found for OW permits with a GVW between 110,000 lb and 130,000 lb. The differences were due to variations in axle types and configurations. Although a single-axle single-tire is always used as a steering axle, the analyzed OW vehicles might have different combinations of single-duals, tandem, tridem, and quad for the remaining axles. Some configurations were more common than the others, suggesting the need for generating axle configuration distributions. Ranges for GVW, axle type, and corresponding axle loads were identified as part of the analysis.

3.2.1. Gross Vehicle Weight

Figure 3.8 provides an overview of the GVW distribution for the analyzed OW vehicles. Most (over 50%) OW vehicles had a GVW between 100,000-150,000 lb. There were also a considerable number of entries in 80,000-100,000 lb and 200,001-250,000 lb categories. The least frequent category corresponded to OW permits with a GVW greater than 250,000 lb. Again, these OW loads are regarded as SHL vehicles.

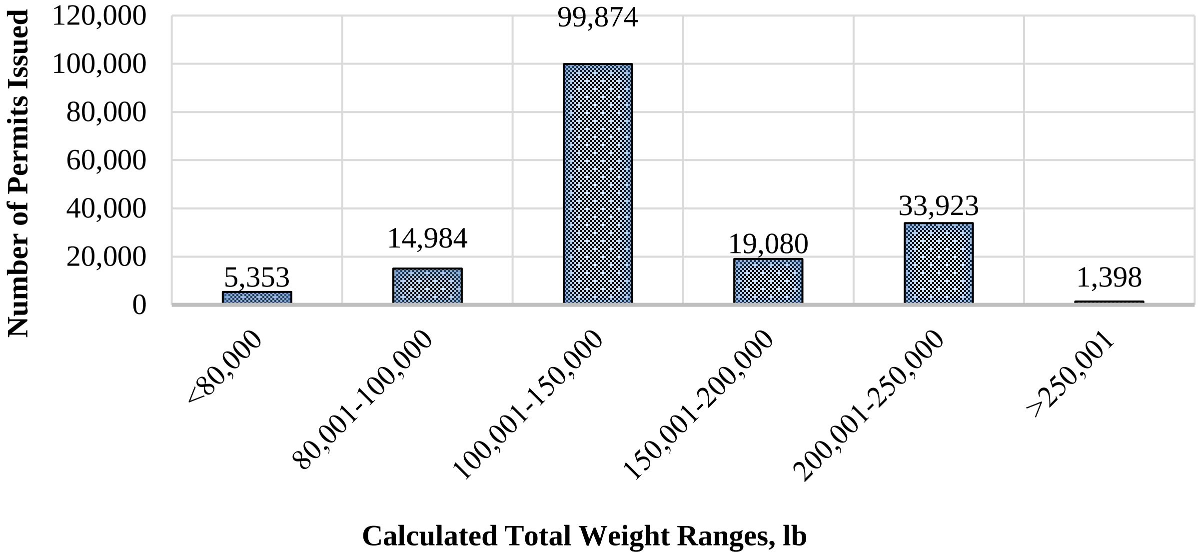


Figure 3.8. GVW distribution of issued OW permits.

3.2.2. Axle Groups Identification

Figure 3.9 shows a copy of a NDOT over-dimensional vehicle permit form. As mentioned before, NDOT provided thousands of forms to be used in the characterization and classification of axle and load configurations. The axle spacing as well as the number of individual axles are included in the permit form. However, the axle group types are not explicitly described. Thus, a manual identification of the axle groups (i.e. single, tandem, tridem, quad) was required for categorization and analysis. To be consistent with pavement performance analysis currently used in ME methodologies, the closely spaced axles with identical properties (i.e., similar axle loading, axle spacing, and tire configuration) were combined into one axle group. As already noted in Section 2.3.1, if the spacing between two adjacent axles is more than the 60 inch, the pavement responses under the first axle do not get affected by the second axle loading (i.e., interaction between axles). Such an observation can be employed to define the axle groups within the OW vehicle configuration.

The sample permit forms were scrutinized for common axle groups used in OW vehicles. For example, although a single-axle with single tires is always used as a steering axle, the analyzed OW vehicles might have different combinations of single, single-duals, tandems, tridems, quads and/or trunnion for the remaining axles. Quads are identified as axles groups with 16 tires and trunnion are identified as axles having non-standard configurations with 16 or more tires. It should be noted that quads and trunnion axle groups were rarely identified in the reviewed issued permits. However, their inclusion in this study was warranted to consider future trends in OW vehicle configurations. Even though trunnion axle groups can contain more than 16 tires, trunnion axles with only 16 tires were included in this study. Figure 3.10 provides a schematic of the most common axle groups identified in the sample permits.

To illustrate the identification of axle groups' process, Figure 3.11 presents a configuration of an OW vehicle as obtained from an actual NDOT permit form. The GVW of the vehicle is above 250,000 lb. The trucking company is required to provide the axle spacing's and number of axles enabling the axle grouping. The vehicle presented in Figure 3.11 contains seven axle groups. Firstly, the steering axle is a single axle with single tires (axle group A). Secondly, a tridem axle (axle group B). Finally, a sequence of five tandem groups (axle groups C, D, E, F, and G) are presented. It should be noted that the spacing between each axle line in the tridem and tandems groups is less than or equal to 60 inch. Each of these groups (tridem and tandems) can be considered a single axle groups for analysis purposes.

NEVADA DOT

NEVADA DEPARTMENT OF TRANSPORTATION
1263 South Stewart Street, Carson City, Nevada 89712, 800-552-2127/775-888-7410

OVER-DIMENSIONAL VEHICLE PERMIT

Permit #
NDOT42771

Permit Type: TRIP - 5 DAY @ $25 GENERAL BILLING

Insurance:

SIERRA RENTAL & TRANSPORT COMPANY INC
1305 KLEPPE LANE
P O BOX 1573
SPARKS, NV, USA 89432

Route: **From:** GOLD HILL, NV - COMSTOCK MINE
To: SPARKS, NV - 600 GLENDALE AVENUE
Over Routes: SR 342, SR 341, US 50, US 395/I-580, GLENDALE

Instructions: **NONE REQUIRED

Travel: FROM 5/20/2014 THRU 5/24/2014

Authorized: ☑ Weekend ☑ Night ☑ Holiday ☑ Workday Commute Hour

Description of Load: HAUL
CAT 740 ROCK TRUCK

Dimensions: **Width:** 12' 0" **Height:** 15' 0" **Length:** Legal

Gross Weight: 128,700 **Total Axles:** 5 **Overhang:** **Front:** Legal **Rear:** Legal

Axle Spacing	1	14' 0"	2	4' 6"	3	29' 6"	4	6' 0"	5
Wheels	4		4		4		4		8
Wgt	21,600 (Steer weight)			46,725				60,375	

Figure 3.9. NDOT over-dimensional permit sample.

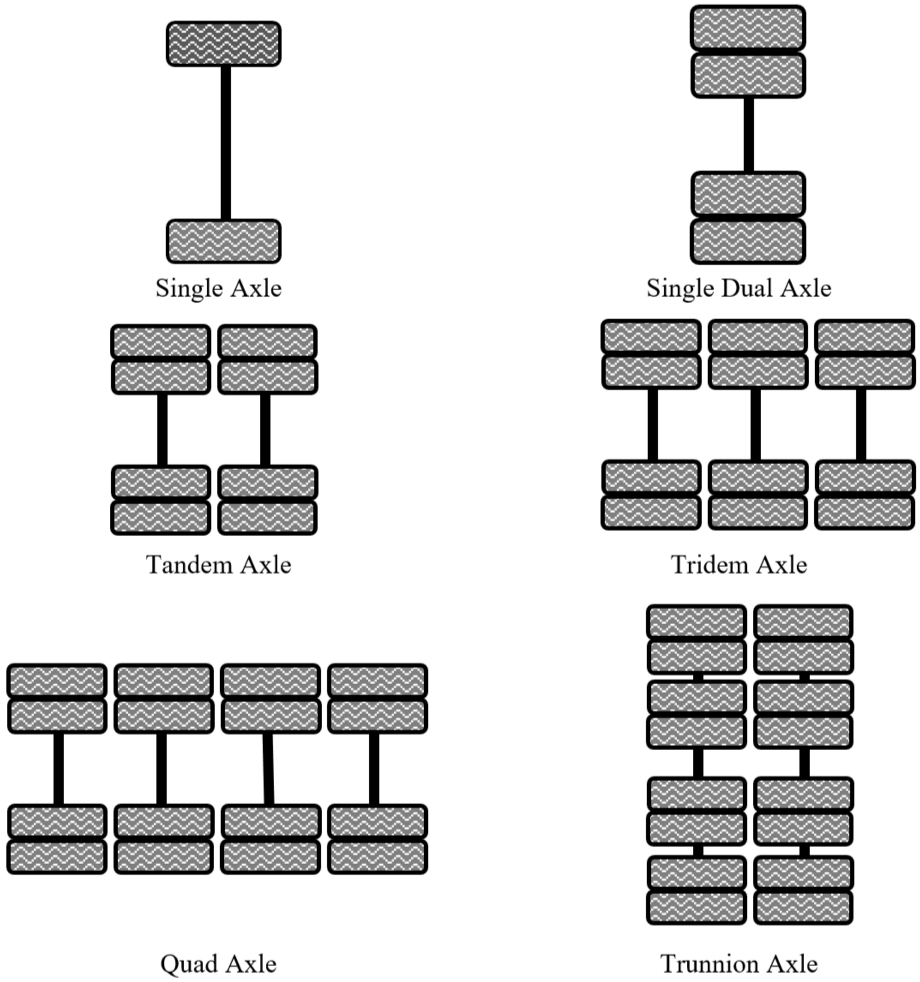


Figure 3.10. Identified axle group types in NDOT OW vehicle permits.

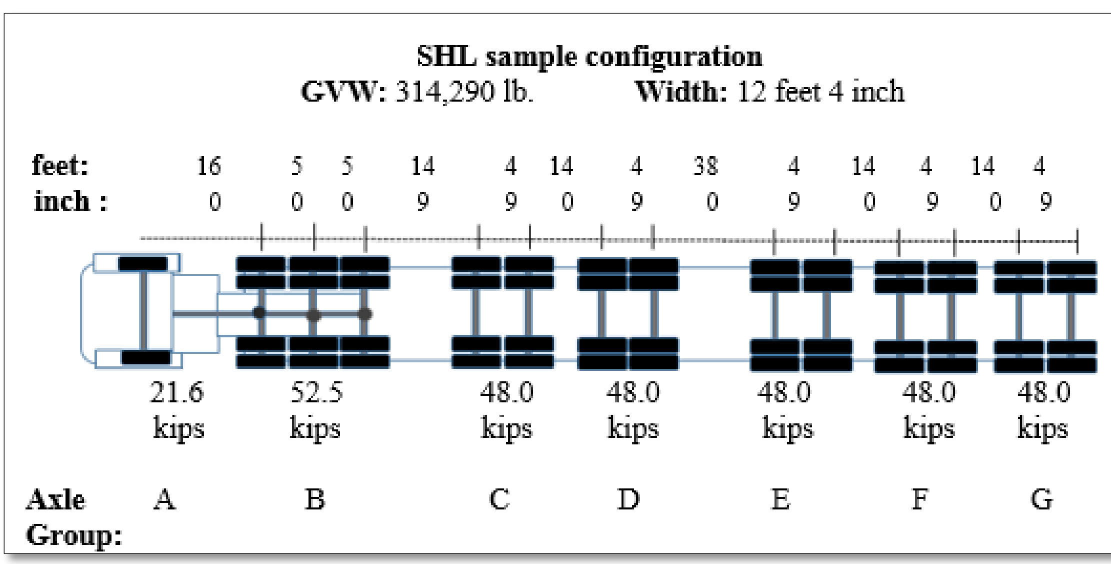


Figure 3.11. Configuration of a permitted OW vehicle.

3.2.3. Axle and Tire Load Distributions

NDOT permit forms contained the axle weight for the different axle groups (see Figure 3.9). After axle grouping of all permit forms provided by NDOT was completed, a descriptive statistical analysis was conducted. This was done to identify statistical parameters that could describe the distributions of the identified axle groups. For instance, Figure 3.12 presents a boxplot representation of axle groups' distributions. Here, the single axle group exhibited the lowest load range with a maximum load up to 23,000 lb. On the other hand, the quad and trunnion axle groups, which were grouped together in this figure, presented the highest load range with loads as high as 75,000 lb. It is noted that the load range of the single dual axle group (4 tires) is not too far from the single axle. Similarly, the ranges of tandem and tridem groups containing eight and twelve tires, respectively, are not too far from each other either. The horizontal bar inside the boxplots represents the respective median value for the load. As expected, the median axle group load increases from single axle to quad/trunnion axle groups. Table 3.2 presents a descriptive statistical summary of axle groups' loads. This table provides the minimum, maximum, median, mean as well first and third quartiles (25th and 75th). The information presented in this section was essential in the design process of the pavement analysis experimental program, which is described later on in this report.

The number of tires per individual axle is also provided in the permit forms. Using the identified number of tires and corresponding axle group weights, the load corresponding to each individual tire within an axle group was identified. Figure 3.13 provides a boxplot representation of the tire load distributions. Counterintuitively, the highest loads per tire corresponded to the single axle and the lowest to the quad and trunnions axle groups. This is mainly due to the number of tires included in these axle groups. For instance, the maximum single axle load was 23,000 lb (see Figure 3.12). Thus, the load per tire corresponds to 11,500 lb, which is considerably high. On the other hand, the 75,000 lb quad axle load is distributed over 16 tires, wich resulted in a tire load of only 4,688 lb. Table 3.3 provides a descritptive statistical summary of the tire load distributions of the identified axle groups.

Table 3.2. Descriptive Statistical Summary of Axle Groups from OW Permit Samples.

Axle Group	Mean	Minimum	Quartile 1	Median	Quartile 3	Maximum
Single	16,519	12,000	12,500	15,000	19,200	23,000
Single Dual	24,012	18,000	21,000	24,000	28,000	29,000
Tandem	46,442	22,000	46,200	46,725	52,041	65,000
Tridem	54,359	30,957	50,750	58,000	60,000	65,525
Quad/Trunnion	60,242	45,500	54,167	60,000	66,000	75,000

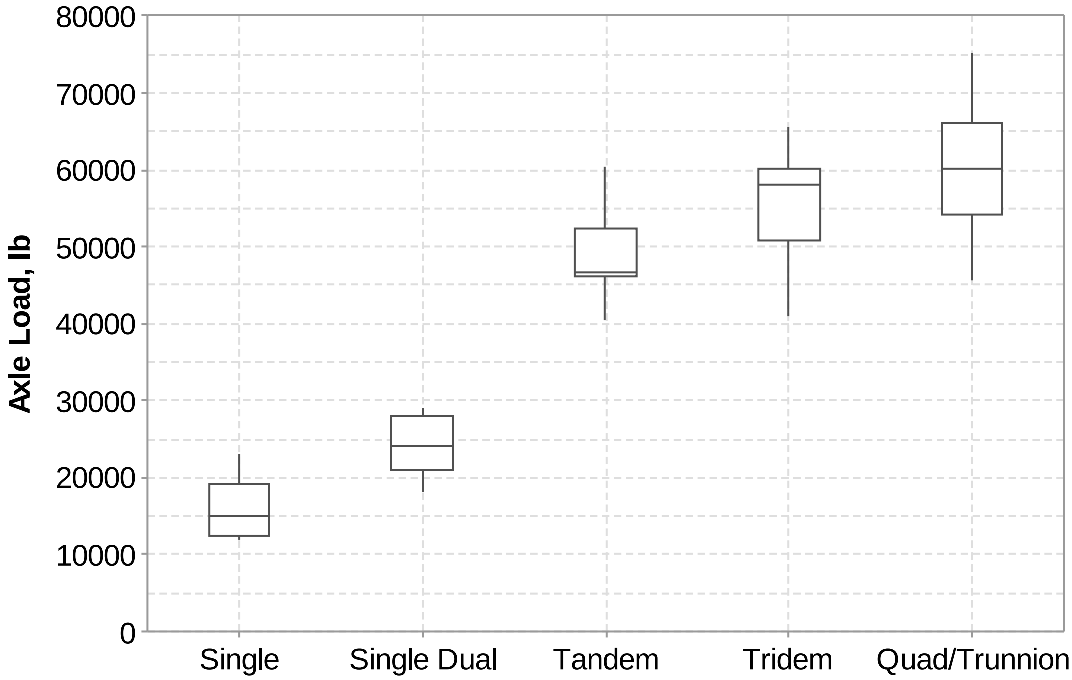


Figure 3.12. Boxplot representation of load distributions for axle groups.

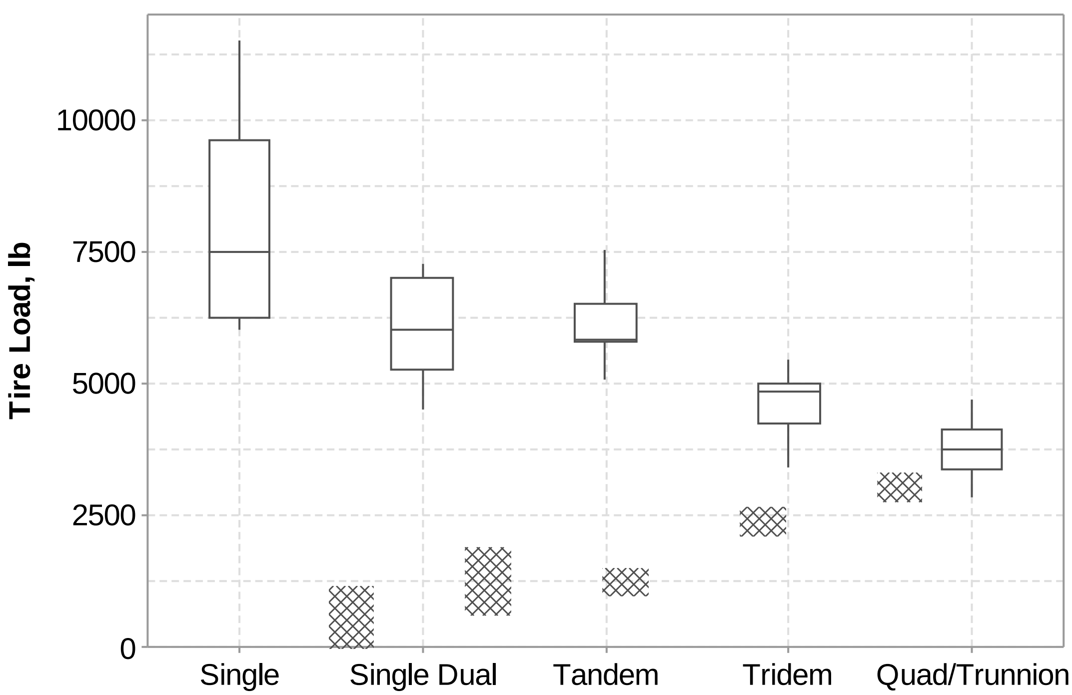


Figure 3.13. Boxplot representation of tire load distributions.

Table 3.3. Descriptive Statistical Summary of Tire Loads from OW Permit Samples.

Axle Group	Mean	Minimum	Quartile 1	Median	Quartile 3	Maximum
Single	8,260	6,000	6,250	7,500	9,600	11,500
Single Dual	6,003	4,500	5,250	6,000	7,000	7,250
Tandem	5,760	2,750	5,775	5,841	6,505	8,125
Tridem	4,529	2,580	4,229	4,833	5,000	5,460
Quad/Trunnion	3,765	2,844	3,385	3,750	4,125	4,688

3.3 Climatic Zones in Nevada

Since the proposed analysis uses a ME approach to estimate pavement damage, the pavement temperature at the time of the OW movement becomes a critical factor that needs to be considered. The collected NDOT database and sample permits included date, origin, destination and routing of OW vehicle. These entries can be used to identify the climate characteristics that accompanied the OW vehicle during operation. For instance, if an OW movement is occurring during the month of January in the greater Reno area, low pavement temperatures are then expected during the move. On the other hand, if the OW movement is occurring in the month of July in the Las Vegas area, extremely high temperatures are then expected.

3.3.1. Weather Stations

NDOT has three districts under its jurisdiction: District I (Representing southern Nevada and headquartered in Las Vegas), District II (Representing northwest Nevada and headquartered in Reno), and District III (Representing northeast Nevada and headquartered in Elko). The environmental conditions vary significantly between NDOT districts; thus, different climatic stations representing the various environments found in Nevada were implemented in the analysis. The required climatic input data were retrieved from Long-Term Pavement Performance (LTPP) weather stations in Nevada. Table 3.4 presents the Nevada weather stations considered in this study. It should be noted the wide range of mean annual pavement temperatures found at different geographical locations within Nevada. As expected, the maximum mean annual air temperature is observed in Las Vegas. This location presents the lowest elevation as well. On the other hand, the lowest mean annual air temperatures were found in South Tahoe and Winnemucca.

NDOT has also divided District I and District III into subdistricts. District I is divided in Las Vegas and Tonopah sub districts. District III is divided in Elko, Winnemucca, and Ely sub districts. Figure 3.14 is a map representation of NDOT subdistricts and the NDOT highway system.

Table 3.4. NDOT Weather Stations Considered in the Study

Location	Elevation, Feet	LTPP Weather Station Description	Estimated Mean Annual Pavement Temperature, °F	NDOT District
Elko	5,050	Elko Regional Airport	54	3
Ely	6,248	Ely Airport	52	3
Las Vegas	2,186	McCarran International Airport	81	1
Lovelock	3,902	Derby Field Airport	58	2
Mercury	3,230	Desert Rock Airport	70	1
Reno	4,410	Reno Tahoe International Airport	64	2
South Tahoe	6,260	Lake Tahoe Airport	50	2
Tonopah	6,047	Tonopah Airport	61	1
Winnemucca	4,296	Winnemucca Municipal Airport	48	3

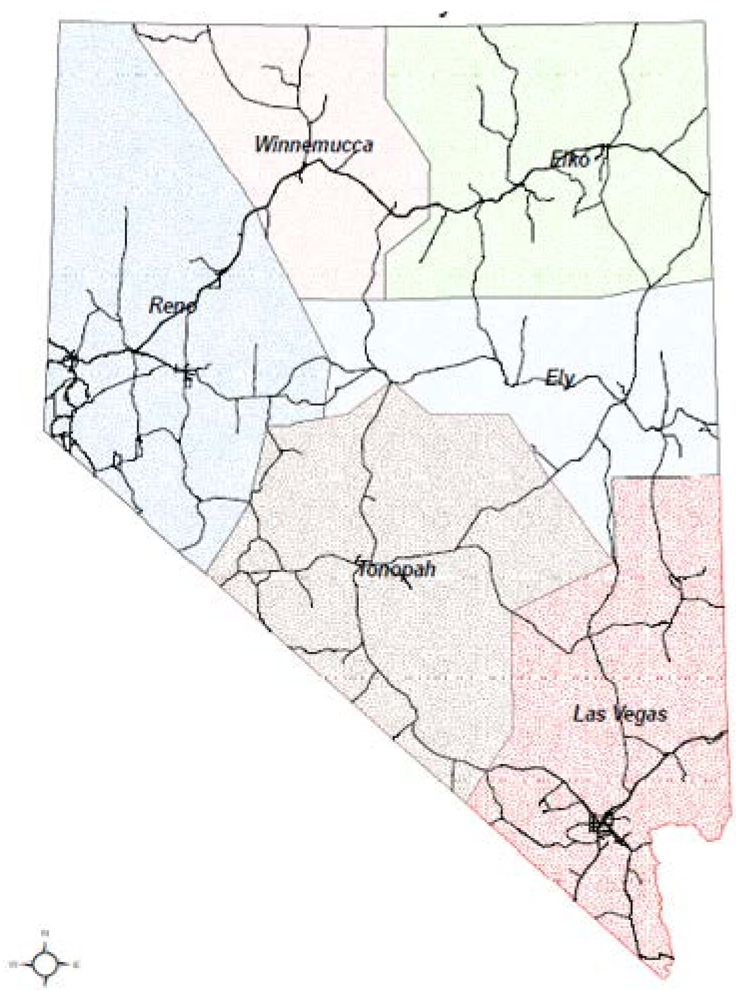


Figure 3.14. Map of NDOT road system and subdistricts.

3.3.2. Estimated Pavement Temperature

Climatic factors are major inputs in pavement analysis and design. Because pavement temperature affects AC dynamic modulus, it subsequently influences AC critical responses. Thus, the proper characterization of climatic conditions and more particularly, AC layer temperature is essential. This section presents information about the pavement temperature profiles used in this study.

Complete hourly-annual air temperature profiles and other climatic information were used to estimate pavement temperature profiles for the various locations in Nevada. The model developed by Alavi et al. was used to accomplish this goal.(56) This one-dimensional model is based on the finite-volume control method (FVCM) and requires inputs of climatic data (solar radiation, air temperature, and wind speed), material thermal properties (density, specific heat capacity, and thermal conductivity), and surface characteristics (albedo, emissivity, and absorption). Input climatic data were obtained from each of the different Long Term Pavement Performance (LTPP) weather stations. The output of the prediction model was spatial pavement temperature as a function of depth on an hourly basis for the various geographical locations in Nevada. The AC mid-depth temperature was selected as a representative AC temperature in this study. Figure 3.15 and Figure 3.16 show the estimated mid-depth AC temperature of pavement sections located in Las Vegas and South Tahoe, respectively. A large difference between both pavement temperature profiles is observed. For instance, the mid-depth AC temperature in July in Las Vegas reaches values over 120°F, while the maximum mid-depth AC temperature in South Tahoe remains below 100°F. On the other hand, significantly lower temperatures are estimated for South Tahoe when compared to Las Vegas location. The estimated temperature profiles for the remaining stations can be found in Appendix A.

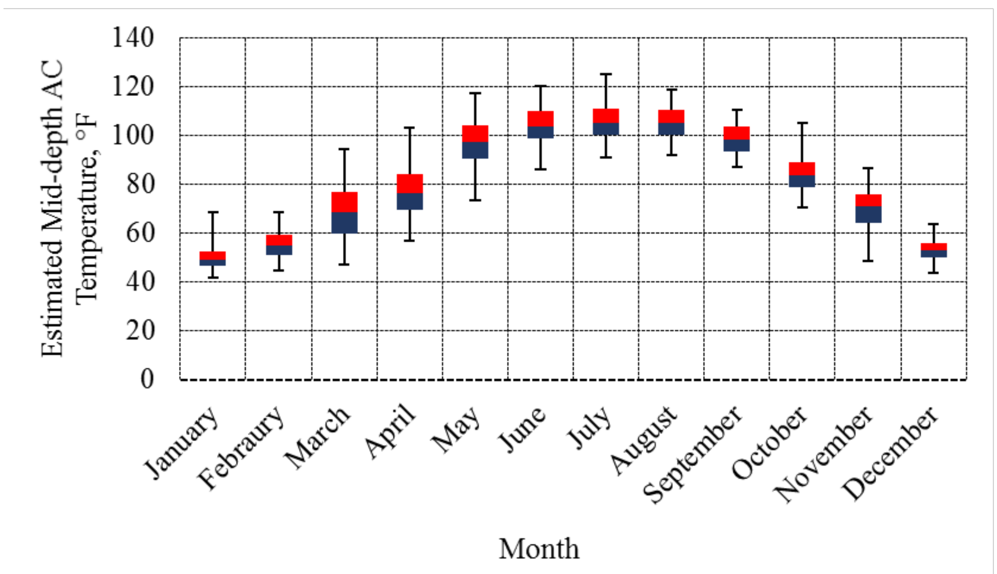


Figure 3.15. Estimated mid-depth AC temperature for Las Vegas.

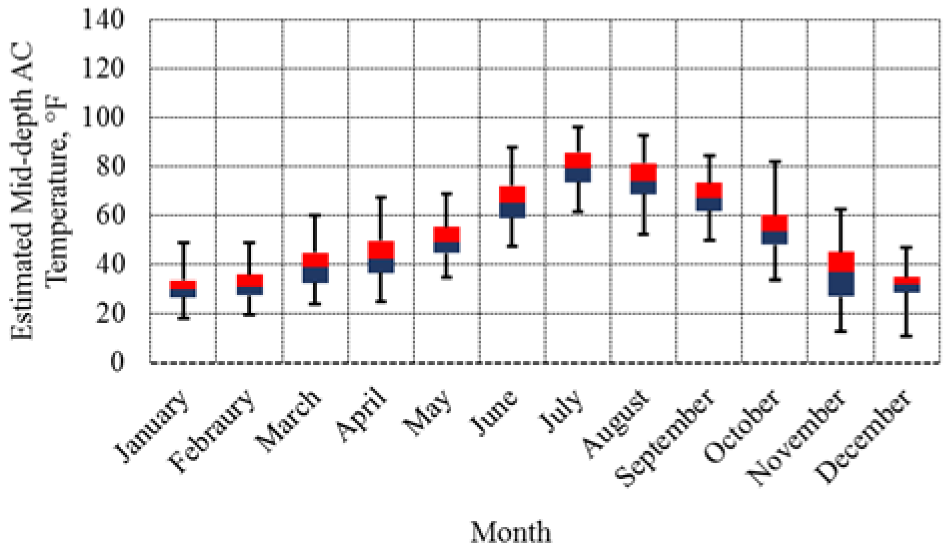


Figure 3.16. Estimated mid-depth AC temperature for South Tahoe.

3.4 Pavement Structures and Materials

Different pavement structures were used to represent typical pavement sections found on NDOT highway system. Table 3.5 presents seven different pavement structures, which were selected as representative pavement sections in this study. The structure with the maximum structural capacity corresponds to 10 inch AC over 10 inch CAB over a SG. Two structures using road bed modification (RBM) layers instead of CAB layers were also included. The pavement sections presented in Table 3.5 were implemented on all NDOT districts.

Table 3.6 shows representative material properties which are typically used in the ME design process of pavement structures in Nevada.[52] The standard NDOT dense-graded polymer-modified asphalt mixtures were used for the AC layer. Specifically, Type 2C with PG76-22NV for District I and Type 2C with PG64-28NV for Districts II and III. Representative dynamic modulus and phase angle data for dense-graded asphalt mixtures were obtained from the NDOT ME Design Manual.[52] Typical resilient moduli of 44,000 psi; 30,000 psi; and 15,000 psi were used for RBM, CAB and SG, respectively. More details about the selected properties can be found in the *NDOT Manual for Designing Flexible Pavements Using AASHTOWare Pavement-ME*.[52]

Table 3.5. Representative Pavement Structures Used in Study.

Pavement Structure	**Layer Thickness, inch**		
	AC	CAB	RBM
Structure 1	3.0	Not Applicable	4.0
Structure 2			6.0
Structure 3	6.0	6.0	Not Applicable
Structure 4		10.0	
Structure 5	8.0	8.0	
Structure 6		10.0	
Structure 7	10.0	10.0	

Table 3.6. Representative Pavement Material Properties.

Pavement Layer	Modulus		Material Characterization
	NDOT District I	District II and III	
Asphalt Concrete (AC)	Dynamic Modulus of Type 2C with PG76-22NV Mixture	Dynamic Modulus of Type 2C with PG64-28NV Mixture	Viscoelastic
Crushed Aggregate Base (CAB)	E_{CAB}= 30,000 psi		Linear Elastic
Road Bed Modification (RBM)	E_{CAB}= 44,000 psi		Linear Elastic
Subgrade (SG)	E_{SG} = 15,000 psi		Linear Elastic

CHAPTER 4 DATABASE OF CRITICAL PAVEMENT RESPONSES

A database of pavement responses was required to model pavement damage attributable to OW vehicle moves. The database includes critical pavement responses, namely, vertical compressive strain at mid-depth (ε_r) of AC layers and maximum horizontal tensile strain at bottom of AC layers (ε_t) to model AC permanent deformation and AC bottom-up fatigue cracking, respectively. The 3D-Move *version 2.1* software was used to determine the pavement responses under multiple loading and environmental conditions. The primary reason for calculating ε_r and ε_t was to estimate the number of repetitions to failure for the analysis OW vehicle as well as the reference vehicle using locally calibrated MEPDG performance models. As presented in Section 2.3, critical pavement responses are needed to estimate pavement performance curves, LEF, and PDAC. Multiple factors that affect pavement responses, including pavement temperature, vehicle speed, and axle load were included in the experimental plan. Chapter 4 summarizes the experimental plan employed to develop a pavement responses database that is used to model AC permanent deformation and AC fatigue cracking attributable to OW vehicle moves.

4.1 Experimental Plan

An experimental plan was developed to generate the critical pavement responses required in this study. An array of axle and tire loading configurations, climatic conditions, material properties, and pavement structures were considered in the development of the pavement responses database. The factors, and their respective applicable range, included in the experimental plan were based on the findings from the review of historical overweight vehicle permits. For instance, the axle types and load ranges identified in Chapter 3 were considered in the full factorial experimental plan shown in Table 4.1.

OW vehicles can have different combinations of single, single dual, tandem, tridem, quad, and trunnion axle groups within their configuration. Table 4.1 shows the six most typical axle groups observed in OW vehicle configurations in Nevada. For instance, the pavement analyses required to model single and single dual axles were conducted over an axle load range of 10,000 to 40,000 lb in 3D-Move Analysis software. Also, the load ranges used for modeling quad and trunnion axles were 20,000 to 80,000 lb. It should be noted that different tire pressures (widebase tires), and a wide range of pavement temperatures and operational vehicle speeds were also considered.

The experimental plan encompasses the typical pavement structures presented in the previous chapter. It should be noted that widebase tires were also taken into consideration. 3D-Move Analysis has the capability of modeling widebase tires with non-uniform stress distributions. Single axle and tandem axles with two and four widebase tires, respectively were modeled. Over 8,000 runs using 3D-Move Analysis software were necessary to fulfill the experimental plan presented in Table 4.1. These runs were used to develop the database of critical pavement responses (ε_r and ε_t) at multiple locations within the pavement structure.

Table 4.1 Experimental Plan for Pavement Responses Database.

Factor	Levels					
Axle Type	Single	Single Dual	Tandem	Tridem	Quad	Trunnion
Axle Load Range, lb	10,000 to 40,000	10,000 to 40,000	20,000 to 70,000	20,000 to 80,000	20,000 to 80,000	20,000 to 80,000
Axle Spacing, inch	Not Applicable	Not Applicable	54	54	54	54
Tire Spacing, inch	Not Applicable	14	14	14	14	14
Tire Type	Single and Widbase[a]					
Tire Pressure, psi	85[b], 120, 130[c]					
Vehicle Operating Speed, mph	1 to 90					
Pavement Temperature, °F	1 to 180					
AC Material	Dense-Graded Type 2C with PG64-28NV Dense-Graded Type 2C with PG76-22NV					
Pavement Structure	1 through 7 (Refer to Table 3.5)					

[a] Widebase tires were considered for single and tandem axles only.
[b, c] 85 and 130 psi tire pressures used on some BRT models.

4.2 Overview of 3D-Move Analysis Software

The 3D-Move Analysis software version 2.1 was used to calculate the critical pavement responses under the various axle configurations. In 3D-Move Analysis the continuum-based finite layer approach is used to evaluate the response of a layered medium subjected to a moving surface load.

3D-Move was used to simulate all moving loads traveling at a constant speed accounting for the moving nature of the OW vehicle load. In addition, in 3D-Move the properties of the AC layer (i.e., dynamic modulus) vary as a function of frequency and temperature accounting for the viscoelastic nature of AC materials. As part of this study, the characterization of the pavement system was conducted through a combination of viscoelastic and elastic horizontal layers for the AC and unbound layers, respectively. Several research studies have validated the use of 3D-Move by comparing 3D-Move calculated pavement responses against responses measured in the field.[57, 58]

As an example, Figure 4.1 presents a schematic of the locations at which the pavement responses were evaluated for a tandem axle group (8 tires per axle). In this figure the X-direction is the direction of traffic. As presented in Figure 4.1, and according to the distress model, responses were evaluated at different depths within the 3 inch AC layer. At each depth, three points (A, B, and C) corresponding to tire centerline, tire edge, and between adjacent tires were included in the pavement analysis. For instance, the three points circled were evaluated at the bottom of the AC layer for the estimation of AC bottom-up fatigue cracking. Pavement responses (ε_t) were obtained for locations A, B and C. However, only the maximum response was used in the estimation of pavement damage and PDAC. Figure 4.2 provides the response history of the maximum tensile strain located at point C (between the two adjacent tires). It should be noted that in 3D-Move Analysis, only one side of the entire axle is typically modeled.

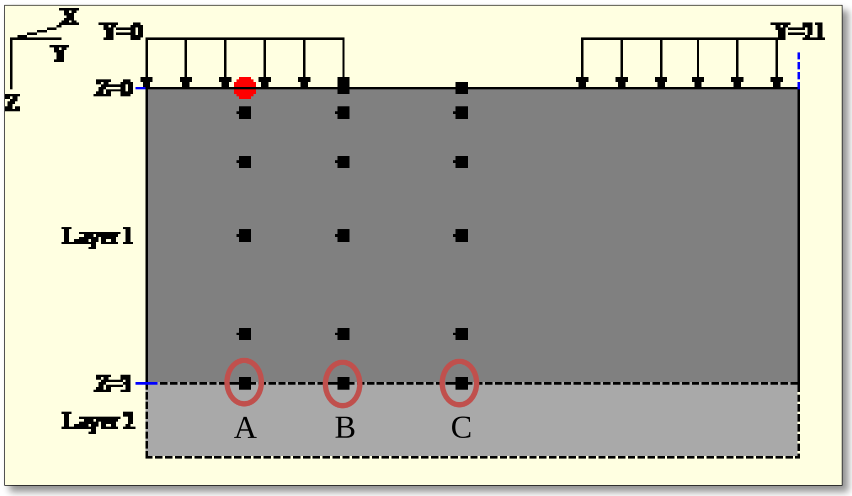


Figure 4.1. Schematic of 3D-Move analysis of a tandem axle group at six different pavement depths.

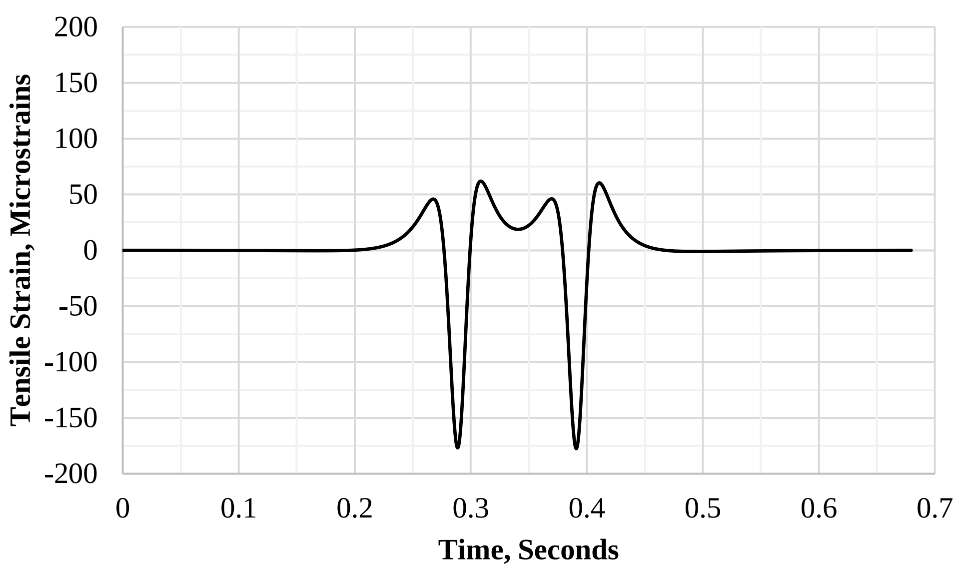


Figure 4.2. Tensile strain history at bottom of AC layer at C location (between adjacent tires).

4.3 Pavement Response Database

The vertical compressive strain at mid-depth (ε_r) of AC layers and maximum horizontal tensile strain at bottom of AC layers (ε_t) were particularly evaluated as they are used to model AC permanent deformation and AC fatigue cracking, respectively. The pavement responses database was populated by conducting 3D-Move Analysis for the pavement structures and the various factors presented in the experimental plan (Table 4.1).

The flexibility of the 3-D Move Analysis software to account for viscoelastic properties of the AC layer allowed for the determination of PDAC for wide ranges of input values. In fact, the vehicle speed and the mid-depth AC layer temperature were both assessed in this study. As presented in the experimental plan, the operational speed ranged from 1 to 90 mph. Similarly, the mid-depth AC layer temperature ranged from 1 to 180°F, covering all possible scenarios in Nevada. Furthermore, asphalt mixture properties corresponding to typically used materials in Nevada were used.

Relationships between the AC dynamic modulus master curve and the respective pavement responses at different locations within the structure were observed during the analysis of the data. These relationships, which were influenced by the combined effects of loading frequency, temperature, and surface load level, were examined and used in the analysis of pavement responses. These findings helped in reducing the number of 3D-Move Analysis runs required to achieve the objectives of the project.

4.4 Summary

This section presented information about the development of a comprehensive pavement responses database. The database included critical pavement responses (e.g., ε_r and ε_t) to model AC permanent deformation and AC bottom-up fatigue cracking. The 3D-Move Analysis software *version 2.1* was used to determine pavement responses under different loading and environmental conditions. An experimental plan consisting of an array of factors was executed using the 3D-Move Analysis software. This resulted in more than 8,000 runs to determine pavement responses under a variety of loading configurations, material properties, and pavement structures.

CHAPTER 5 PAVEMENT DAMAGE ASSOCIATED COSTS IN NEVADA

As mentioned before, OW movements in Nevada can be classified as single-trip or multi-trip. Although the same cost allocation methodology is used to determine PDAC for both scenarios, the necessary steps to conduct the analysis are different. Figure 5.1 provides a schematic of the steps needed to estimate pavement damage and PDAC for both single and multi OW trip scenarios. For instance, the single trip analysis is based on a deterministic approach which will result in a determined value for PDAC. On the other hand, pavement damage and PDAC for multi-trip permitted OW vehicles are addressed with a probabilistic approach using Monte-Carlo (MC) simulations, which will produce distributions of possible outcome values for LEF and PDAC. Through the MC simulations, the operation of OW vehicles under different conditions and over the duration of the permit (e.g., annual, semi-annual) is considered. This chapter provides detailed information on the estimation of pavement damage and PDAC for both single and multi OW trips.

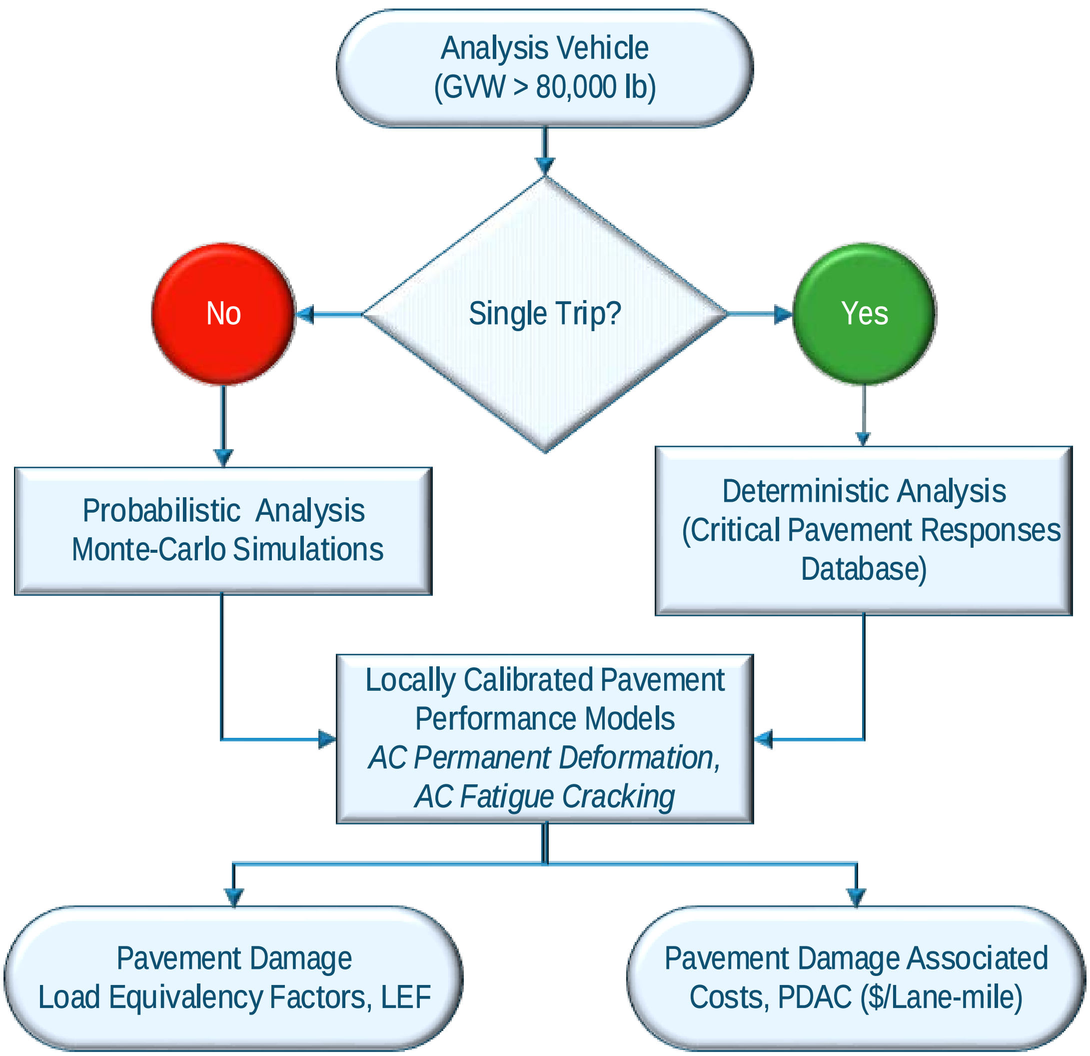


Figure 5.1. Overall methodology for determining pavement damage and PDAC.

5.1 Deterministic Analysis

The deterministic analysis estimates potential pavement damage and PDAC caused by a single pass of an OW vehicle. This type of analysis can be used for single-trip permit scenarios. As part of the single-trip permit request, the GVW, axle and load configurations, route identification, and time and date of the OW vehicle pass are provided. Figure 5.2 presents a sample of a NDOT single-trip over-dimensional permit form. The information presented in the permit allows for the estimation of the necessary inputs to conduct a deterministic analysis for PDAC. For instance, the permit provides information that can be used to estimate the pavement structure, the area in which the OW vehicle operates, pavement temperature, GVW, and axle configuration. Therefore, using appropriate information, the critical pavement responses can be directly estimated from the pavement responses database. The next step in the approach is the implementation of the locally calibrated performance models to estimate the number of repetitions to failure for both the OW and reference vehicles. The last step in the single-trip approach is the determination of LEF as well as the PDAC using the presented cost allocation methodology (refer to Section 2.3).

NEVADA DOT

NEVADA DEPARTMENT OF TRANSPORTATION
1263 South Stewart Street, Carson City, Nevada 89712, 800-552-2127/775-888-7410
OVER-DIMENSIONAL VEHICLE PERMIT

Permit #
NDOT29863

Permit Type: TRIP - 5 DAY @ $25 GENERAL CREDIT CARD

Insurance:

SAMMONS TRUCKING INC
3665 WEST BROADWAY
MISSOULA, MT, USA 59808

Route: **From:** HALLECK, NV - CR 703 & HOPPER ROAD
To: NEVADA/UTAH LINE
Over Routes: HOPPER ROAD, CR 703, SR 229, I-80

Instructions: **PERMITTEE MOVING LOAD FOR T-FORCE–THEY HAVE AN ARRANGEMENT FOR NO HIGHWAY PATROL ON SR 229

Travel: FROM 7/5/2014 THRU 7/9/2014

Authorized: ☑ Weekend ☑ Night ☐ Holiday ☐ Workday Commute Hour

Description of Load: HAUL
PONY SUB

Dimensions: **Width:** 12' 0" **Height:** 15' 0" **Length:** 80' 0"

Gross Weight: 119,750 **Total Axles:** 6 **Overhang:** **Front:** Legal **Rear:** 5' 0"

Axle Spacing	1	18' 0"	2	5' 0"	3	31' 0"	4	5' 0"	5	5' 0"	6
Wheels	4		4		4		4		4		4
Wgt	12,500 (Steer weight)		47,250				60,000				

Pilot Cars Required: **Fore:** NONE REQUIRED
Aft: NONE REQUIRED

Figure 5.2. Sample NDOT over-dimensional permit for single-trip scenario.

5.2 Probabilistic Analysis

The probabilistic analysis was implemented to model multi-trip OW movements. As mentioned before, multi-trip permits authorize a specific OW vehicle to operate without restriction for the duration of the permit. The probabilistic analysis considers multiple factors influencing pavement damage including pavement temperature and pavement structure. MC simulation method was employed to obtain the distributions of output parameters such as AC critical responses, LEF, and PDAC. This simulation method uses random sampling of input parameters based on their distribution.[59, 60] In this study, influential input parameters such as GVW, axle configuration, axle weight, pavement structure, and pavement temperature were used in the MC simulations. After each simulation step, the number of repetitions to rutting and fatigue-cracking failure were calculated for OW and reference vehicles. A MATLAB application was developed to make the execution of MC simulations more efficient. In addition, parallel processing was used to accelerate simulation time because simulation steps could be executed independently.[61] Thousands of simulations were conducted for each of the seven Nevada weather stations presented in Section 3.3.4. It should be mentioned that pavement temperature distributions used in the Monte-Carlo simulations were based on the respective weather stations.

Again, findings from the OS/OW permit database and permit forms were essential in developing the distributions of the input factors for the MC simulations. The database was scrutinized to only select entries containing all the influential input parameters. Specifically, these entries contained information on GVW, axle configuration, axle weight distribution, and routing. As the environmental conditions vary significantly between NDOT districts, the variation was accounted for in the MC simulations.

As presented in Table 2.6, NDOT categorizes roads into five different categories. However, in the probabilistic analysis, only 3 road categories (1, 2, and 3) were taken into consideration, namely highways and freeways (NDOT road category 1), major arterials (NDOT road category 2), and collectors (NDOT road category 3). It was assumed that OW vehicles do not operate on roads with lower structural capacity (e.g., local roads). Based on the last Nevada cost allocation study, highways and freeways are exposed to 59% of overall OW VMT making road category 1 the most common road type in which OW vehicles operate in Nevada.[62] Furthermore, OW traffic VMT is almost equally divided between other the road categories with 20% and 21% on road categories 2 and 3, respectively. This VMT distribution was used to randomly assign road category in each simulation step. Therefore, the pavement structures consisting of 10, 8, and 6 inch of AC over 10 inch of CAB on top of SG were considered for road categories 1, 2, and 3, respectively.

It should be noted that in the probabilistic analysis, the respective material properties for each NDOT district were implemented according to the location of the weather station. For instance, District I material properties were used for Las Vegas, Mercury and Tonopah climatic stations. District II material properties were used for Reno, Lovelock and South Tahoe stations. Finally, District III material properties were used for Elko, Ely, and Winnemucca stations. The variation in the AC mid-depth temperature was also considered in the probabilistic analysis. The model explained in Section 3.3.5 was used to estimate the mid-depth AC temperature for each simulation.

5.2.1. Distribution of Influential Input Parameters

Figure 5.3 presents the distributions of the influential input parameters involved in the probabilistic analysis. For each of these inputs, corresponding data were translated into histograms. Probability distribution functions (PDFs) were calculated based on the frequency of histogram bins. Subsequently, cumulative distribution functions (CDFs) were derived by integrating the PDFs.

As presented in Figure 5.3(a), in the MC simulation process, OW vehicles were divided into seven bins based on GVW: 80,000-90,000 lb; 90,000-100,000 lb; 100,000-110,000 lb; 110,000-130,000 lb; 130,000-150,000 lb; 150,000-200,000 lb; and 200,000-250,000 lb. The frequency of each bin is presented based on information retrieved from the NDOT OW database. Consequently, CDF was generated based on the GVW frequency distribution. Figure 5.3(b) presents the distribution of axle configuration, for the GVW bin of 80,000-90,000 lb as an example, as well as its respective CDF. In the last step of determining OW vehicle axle load and configuration, the axle load was randomly assigned based on the empirical axle weight distribution for the particular axle configuration derived from the database. For instance, Figure 5.3(c) presents axle weight CDF for a tandem axle of an OW vehicle within GVW category of 80,000-90,000 lb.

As mentioned before, pavement temperature was another influential factor used for viscoelastic characterization of AC layer. Figure 5.3(d) presents, as an example, the mid-depth AC temperature distribution for District I. Furthermore, Figure 5.3(e) presents VMT frequency distribution and CDF for different NDOT road categories which was used to randomly select pavement structure.

In each simulation step, inputs were randomly sampled from their respective distribution. AC critical responses were estimated for OW and reference vehicles. Then, number of repetitions to AC rutting and fatigue cracking failure were calculated for OW and reference vehicles using the calibrated performance models followed by the calculation of LEF and PDAC values. Figure 5.4 provides a flowchart representation of the steps associated with the use of MC simulation including generating input parameters, simulation process, and generating output parameters for a single simulation step. The distribution of output parameters (i.e., LEF and PDAC) was obtained by running the simulation for 10,000 steps.

Both the deterministic and probabilistic pavement damage methodologies mimic the operation of OW and reference (standard) vehicles, enabling comparison and determination of relative pavement damage factors. NDOT could use the presented methodology to obtain information for regulating OW vehicle operations in terms of OW vehicle axle configurations. It could also be used to limit OW vehicle types operating on specific highway facility. In addition, trucking companies could use the method to optimize vehicle axle configurations and axle loading distributions in order to minimize pavement damage, and consequently increase their revenue by reducing permit fees.

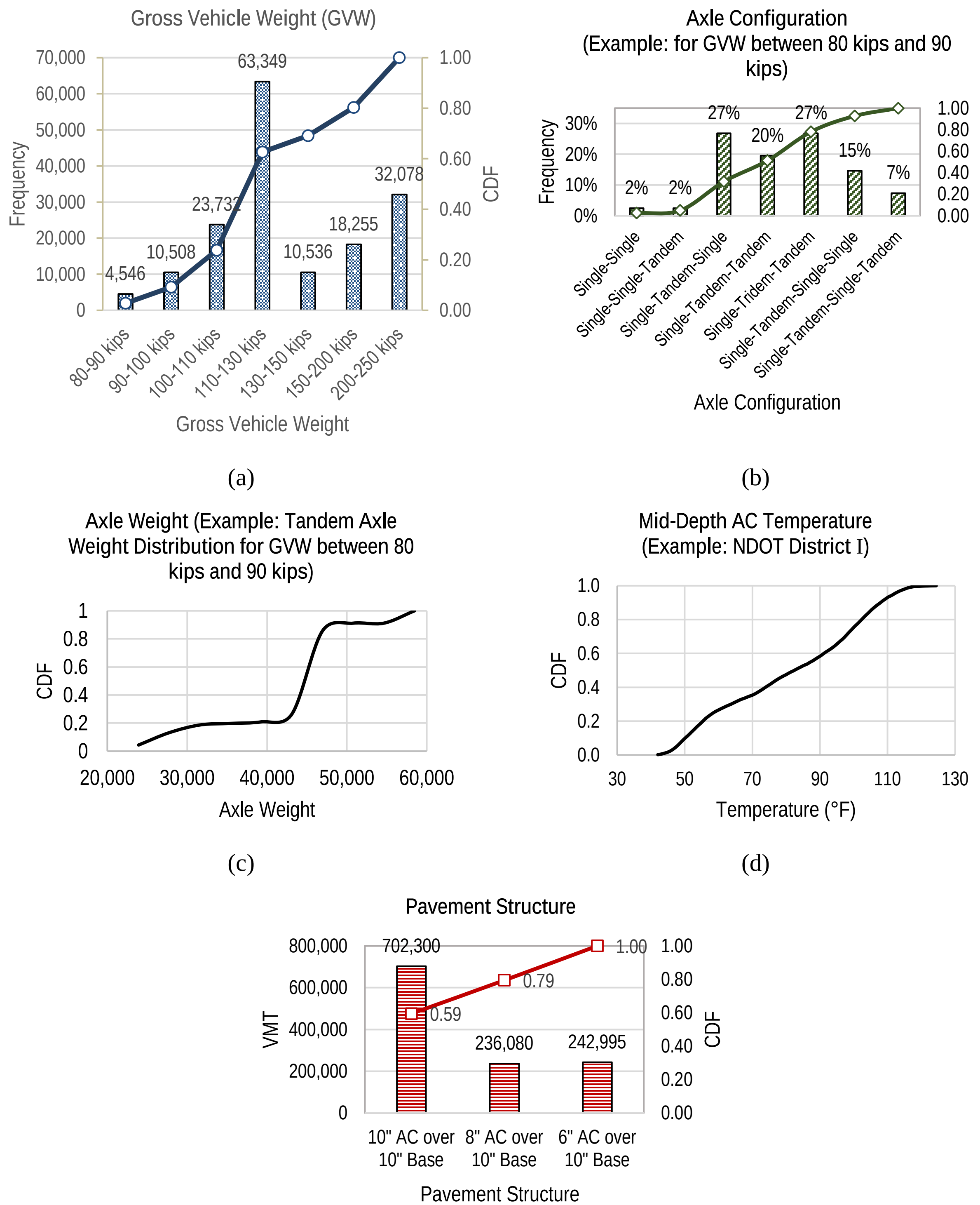


Figure 5.3. Sample input parameters for Monte-Carlo simulation: (a) gross vehicle weight (GVW), (b) axle configuration, (c) axle weight, (d) mid-depth AC temperature; and (e) pavement structure.

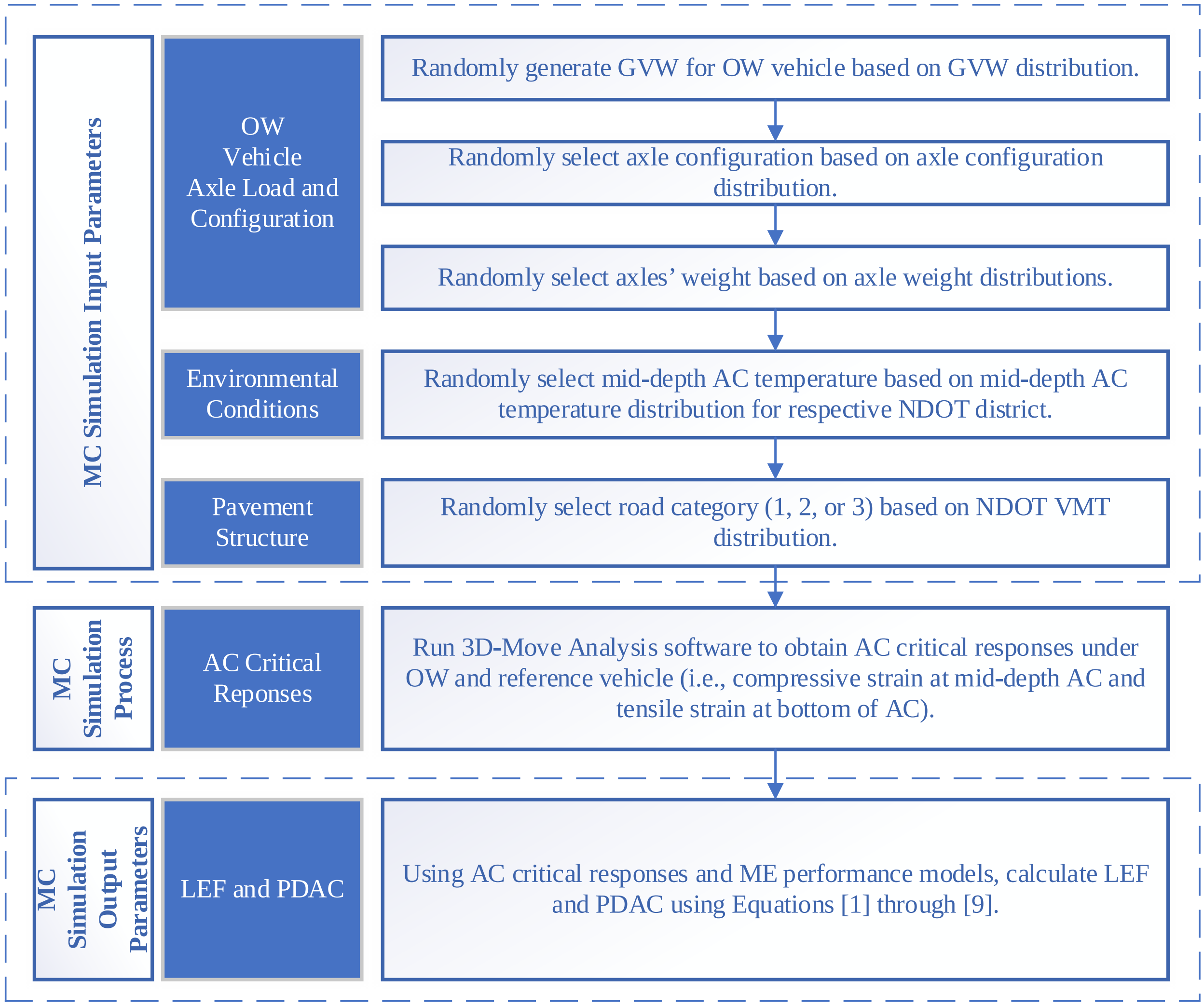


Figure 5.4. Monte-Carlo simulation flowchart presenting inputs, process, and outputs.

It should be noted since SHAs do not usually track the number of OW trips, the number of miles travelled associated to each multi-trip permitted vehicle is unknown. A study conducted by the Ohio Department of Transportation (ODOT) estimated that, on average, 25 individual single-trips are associated with each annual permit.[28, 35] This underscored the significance of the potential pavement damage and associated costs due to multi-trip permits which should not be ignored. However, it also demonstrates the uncertainty associated with multi-trips in general. As the probabilistic analysis presented in this report produces PDAC results in US dollars per lane mile, there is a need to estimate the VMT associated with multi-trip permits. It is suggested that NDOT starts requesting an estimate of the number of miles associated with each multi-trip permitted vehicle during the permit application process. This should be done until a solid distribution of VMT is assembled and included in the probabilistic analysis.

5.3 Probabilistic Analysis PDAC Output Results

Figure 5.5 and Figure 5.6 present probabilistic PDAC output results based on AC fatigue cracking and AC permanent deformation (in logarithmic scale) as a function of mid-depth AC temperature, respectively. These distributions consider all possible cases (OW truck types, GVW levels, and the entire range of pavement temperatures for the Reno weather station). Because of the viscoelastic behavior of AC layers, pavement responses are highly sensitive to pavement temperature. Thus, PDAC values will also be affected by pavement temperature. Maximum PDAC values based on AC fatigue cracking were observed over intermediate pavement temperature ranges. On the other hand, permanent deformation PDAC values increased exponentially with the increase in AC temperature. This is mainly due to the relatively higher stiffness for the AC mixture at lower temperatures, suggesting minimal induced permanent deformation damage under OW vehicles. In contrast, greater pavement damage and attributable PDAC are introduced when OW vehicles operate during higher pavement temperatures.

The PDAC results also reveal the influence of different pavement structures on PDAC prediction. Pavement damage and its associated costs clearly depend on the structural capacity of a pavement section. Higher cost values were observed for pavement sections with the lowest structural capacity (i.e., 6 inch AC over 10 inch CAB) when compared to structures with greater structural capacity (8 inch AC over 10 inch CAB, or 10 inch AC over 10 inch CAB). The probabilistic PDAC output results for all Nevada weather stations are presented in Appendix B.

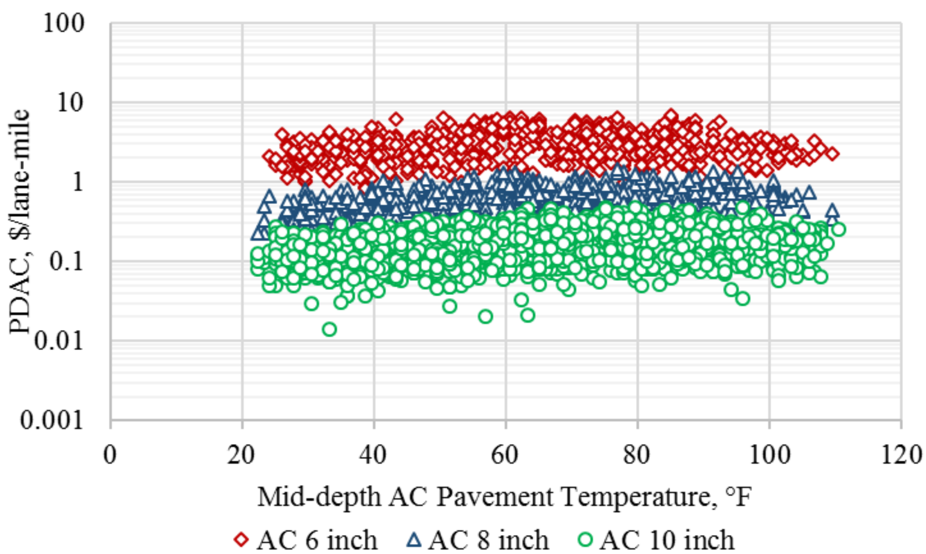


Figure 5.5. AC fatigue cracking based PDAC output from Monte-Carlo simulations for Reno weather station.

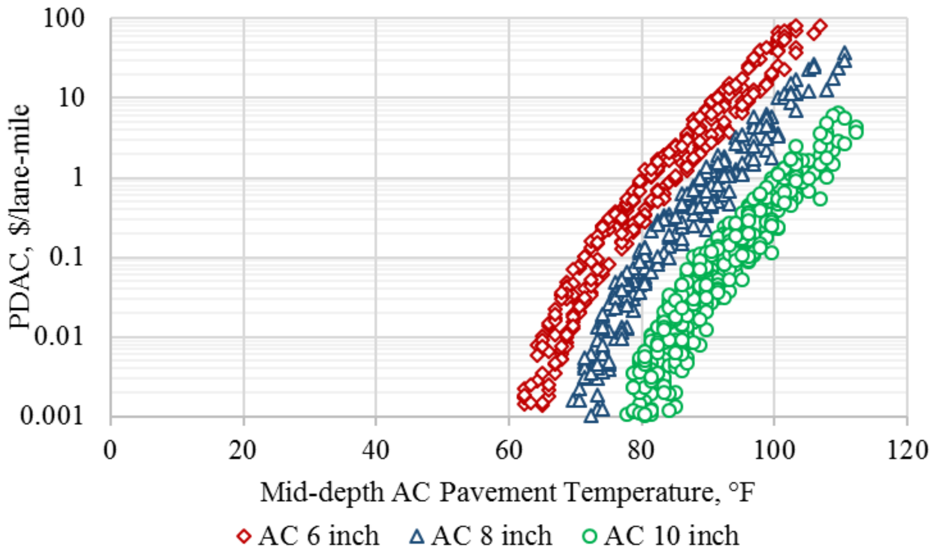


Figure 5.6. AC permanent deformation based PDAC output from Monte-Carlo simulations for Reno weather station.

5.4 Summary

NDOT processes single-trip and multi-trip permits to trucking companies wanting to move OW loads on the Nevada highway system. In this chapter details on the required steps to determine PDAC are presented for both types of permits (single-trip and multi-trip). The deterministic analysis is used for single-trip cases, and uses case-specific input values to evaluate pavement damage and provide a single estimated value for PDAC. As the determination of pavement responses is a necessary step, the pavement responses database is essential in determining critical pavement responses and, consequently, performance models. To estimate pavement damage and PDAC for multi-trip scenarios, a probabilistic analysis using the MC simulation method was employed to obtain the distributions of output parameters such as AC critical responses, LEF, and PDAC. It should be mentioned that the input distributions were based on information evaluated in the NDOT permit database analysis already presented in this report.

CHAPTER 6 IMPLEMENTATION

To accomplish the objectives of this research study, a user-friendly Microsoft Excel package, named *Overweight Vehicle Analysis Package* (OVAP) was developed. The package efficiently conducts pavement damage and PDAC analyses for OW vehicle trips in Nevada. This chapter describes the required information relative to the implementation of this package. The package uses the same information requested by NDOT during the permit application process and comprises of multiple modules found on different sheets. Because the determination of critical pavement responses was a significant aspect of the cost allocation methodology, OVAP included the comprehensive pavement responses database. Therefore, OVAP determines the respective critical responses without conducting individual and time-prohibited pavement analyses for the different axle groups during the OW trip analysis. The package contains different sheets that work together to conduct deterministic (e.g., single-trip scenarios), and probabilistic (e.g., multi-trip scenarios) analyses. The following sections describe the inputs and outputs information for both analysis types. A brief description of user-selected default parameters is also provided.

6.1 Input Information for Deterministic Analysis

The needed input parameters for conducting deterministic PDAC analysis using the *Overweight Vehicle Analysis Package* are presented in this section. Input values are entered in the main sheet named *OW Analysis Package*. Input values are classified in three main categories: *Climatic Information*, *General Analysis Information*, and *Overweight Vehicle Axle Configuration*.

6.1.1. Climatic Information

Table 6.1 summarizes the recommended inputs for the *climatic information* panel. It should be mentioned that inputs in this panel are related to other analysis areas. In fact, output values (e.g. LEF and PDAC) are determined for six different pavement temperature percentiles corresponding to the selected climatic station. Therefore, the user is provided with a wide range of results corresponding to expected temperatures during the month of the OW movement. A careful selection of climatic inputs is necessary. For example, pavement damage caused by an OW vehicle operating during daytime hours may be significantly different than the damage caused by the same vehicle operating during nighttime hours of the same day.

Figure 6.1 depicts the *Climatic Information* input panel. An interactive boxplot chart and a table depicting the range of expected mid-depth AC pavement temperatures according to the user selection of climatic station and month of the move are provided. The user is also given the option to select a mid-depth AC pavement temperature different than those provided in the table of percentiles. Output results are provided for the user-selected analysis temperature also.

Table 6.1. Climatic Information Inputs for Deterministic Analysis.

Parameter	Design Input	Remarks
NDOT District	District I, District II, District III.	User selects from dropdown list the NDOT District that represents the area in which the OW vehicle will operate.
Climatic Station	Elko, Ely, Las Vegas, Lovelock, Mercury, Reno, South Tahoe, Tonopah, Winnemucca.	User selects from dropdown list the climatic station that best represents the geographical area in which the OW vehicle will operate.
Anticipated Time of the Move	Month of the year.	User selects the month of the move from dropdown list.
User Selected Analysis Temperature	Mid-depth AC temperature value from 1-150°F.	User has the option to select a mid-depth AC temperature different than those presented in table of percentiles.

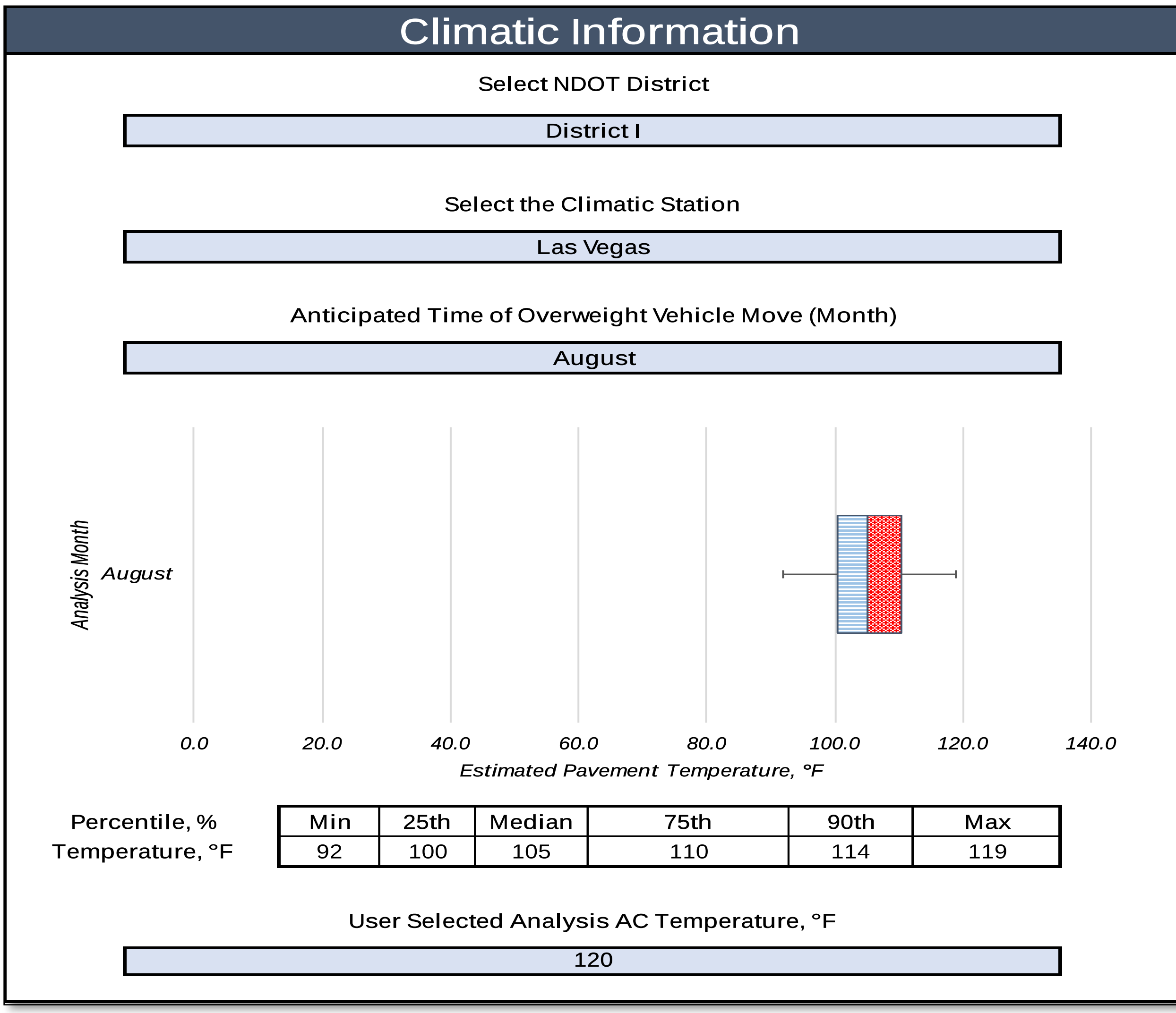


Figure 6.1. Climatic Information input panel for single-trip analysis.

6.1.2. General Analysis Information

This section summarizes the input values of the *General Analysis Information* panel. Table 6.2 describes possible inputs. The information entered in this area is significant as it directly affects output results. For instance, the operational speed of the OW vehicle influences the load-induced pavement responses due to the viscoelastic property of the AC layer. Thus, calculated LEFs and PDAC values are also influenced by the selection of this value. Considering that OW vehicles generally travel at lower speeds, this input needs to be properly selected. Similarly, the user needs to enter the VMT associated with the trip being analyzed. In the case of a single-trip, this information can be easily estimated from the routing provided by trucking companies during the permit application process. Likewise, the user has the option to select from seven different pavement structures the facility that best represents the analysis pavement section. It should be noted that these pavement structures are the same structures included in the experimental plan (see Section 4.1). Lastly, the user needs to input an AADTT value corresponding to the analysis pavement section. Figure 6.2 presents a screenshot of the general information panel.

Table 6.2. Summary of General Analysis Information Inputs.

Parameter	Design Input	Remarks
Operational Speed	Speed value from 1-90 mph.	User inserts an operational speed of the OW vehicle.
Vehicle Miles Traveled	Number of miles. This value should be greater than zero.	User enters the number of miles corresponding to the OW vehicle trip.
Pavement Structure	Seven pavement structures are provided: • 3 inch AC/4 inch RBM • 3 inch AC/6 inch RBM • 6 inch AC/6 inch CAB • 6 inch AC/10 inch CAB • 8 inch AC/8 inch CAB • 8 inch AC/10 inch CAB • 10 inch AC/10 inch CAB	User selects the pavement structure form a dropdown list that represents the pavement section on which the OW vehicle will operate.
Average Annual Daily Truck Traffic (AADTT)	Integer number greater than zero.	User inserts a single representative truck traffic volume for the analysis pavement section.

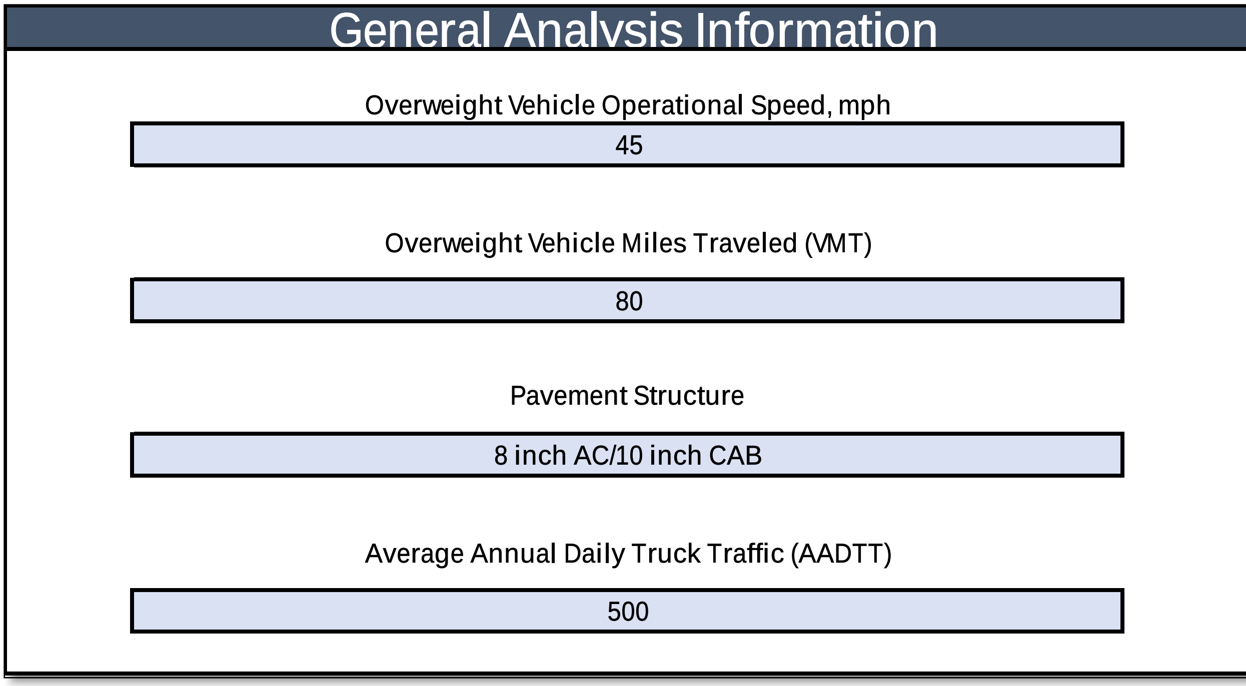


Figure 6.2. General Information input panel.

6.1.3. Overweight Vehicle Axle Configuration

An OW vehicle typically has a length and width larger than a standard truck and it may sometime consume multiple lanes. To analyze the entire OW vehicle, it is first decomposed into different axle groups, and those groups are analyzed independently within OVAP. This assumption relies on the fact that a pavement response at a particular location within the AC layer under a given axle group is not influenced by other adjacent axle groups. In fact, critical pavement responses associated to each axle group are retrieved from the embedded database and used in the calculations.

In the *Overweight Vehicle Axle Configuration* input panel, the user needs to enter the OW vehicle axle/load configuration (e.g. number of axles, axle spacing), the GVW, and the width of the analysis vehicle. The width of the vehicle is an important factor as it is directly factored in the calculation of PDAC for the entire trip. PDAC values are given in US dollars per lane-mile. Thus, vehicles consuming more than one lane (e.g., width > 12 feet), will result in higher PDAC costs for the trip.

Once the axle configuration is entered, a macro activated by the *Axle Grouping* button is used to group the individual axles into the axle groups (e.g., single, single dual, tandem, tridem, quad, etc.). This is done according to the axle spacing, number of tires and a default axle spacing. A default axle distance of 60 inch is used in the package to define the axle groups within the OW vehicle domain. After clicking the *Axle grouping* button the user then enters the load corresponding to each axle group as described on the NDOT over-dimensional permit. Table 6.3 summarizes these inputs. Figure 6.3 presents the *Overweight Vehicle Axle Configuration* panel as found in the package. It should be mentioned that the package is able to analyze OW vehicles containing up to 30 individual axles. In addition, in the axle grouping table, the user can select the implementation of widebase tires for single axles (2 tires) and tandem axles (4 tires).

Table 6.3. Summary of Overweight Vehicle Axle Configuration Inputs.

Parameter	Design Input	Remarks
Gross vehicle Weight	Integer value in lb greater than zero.	This value should be equal to the summation of the individual axle group loads.
Number of Axles	Integer value greater than zero.	Value obtained directly from permit.
Vehicle Width	Integer value in feet greater than zero.	Value obtained directly from permit.
Axle Configuration Table	Axle spacing in feet and inch as well number of tires.	Table is populated from information directly obtained from permit.

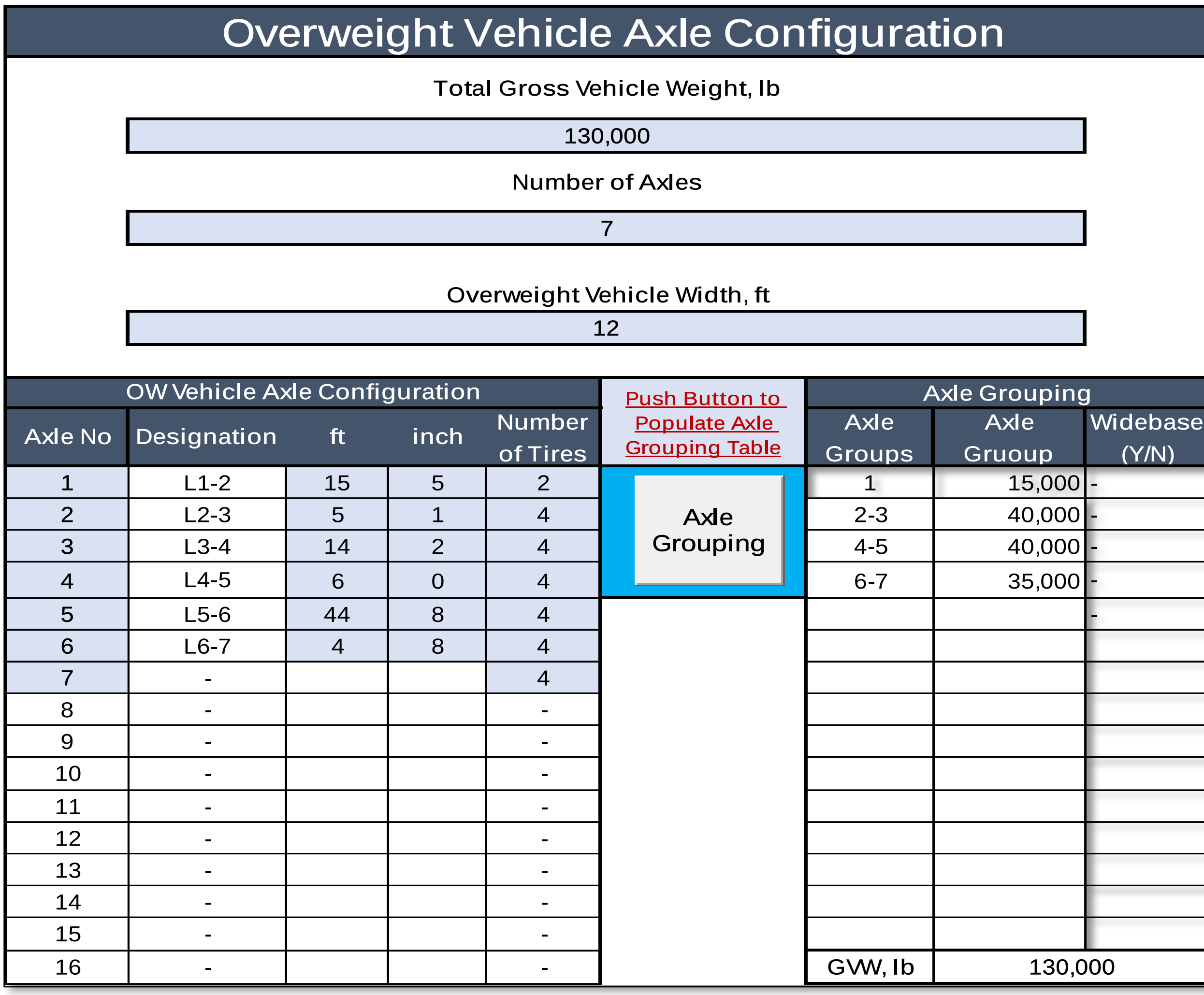


Figure 6.3. Overweight vehicle Axle Configuration input panel.

In addition, the *OW Analysis package* contains a *Supplementary Information* panel that helps the user navigate through the input information. Figure 6.4 depicts an interactive axle configuration plot included as supplementary material. The plot presents the inputted OW vehicle configuration. For instance, the configuration presented in Figure 6.4 has seven individual axles (see Figure 6.3). However, after axle grouping, the package identifies four groups (one single axle, and three tandem axles).

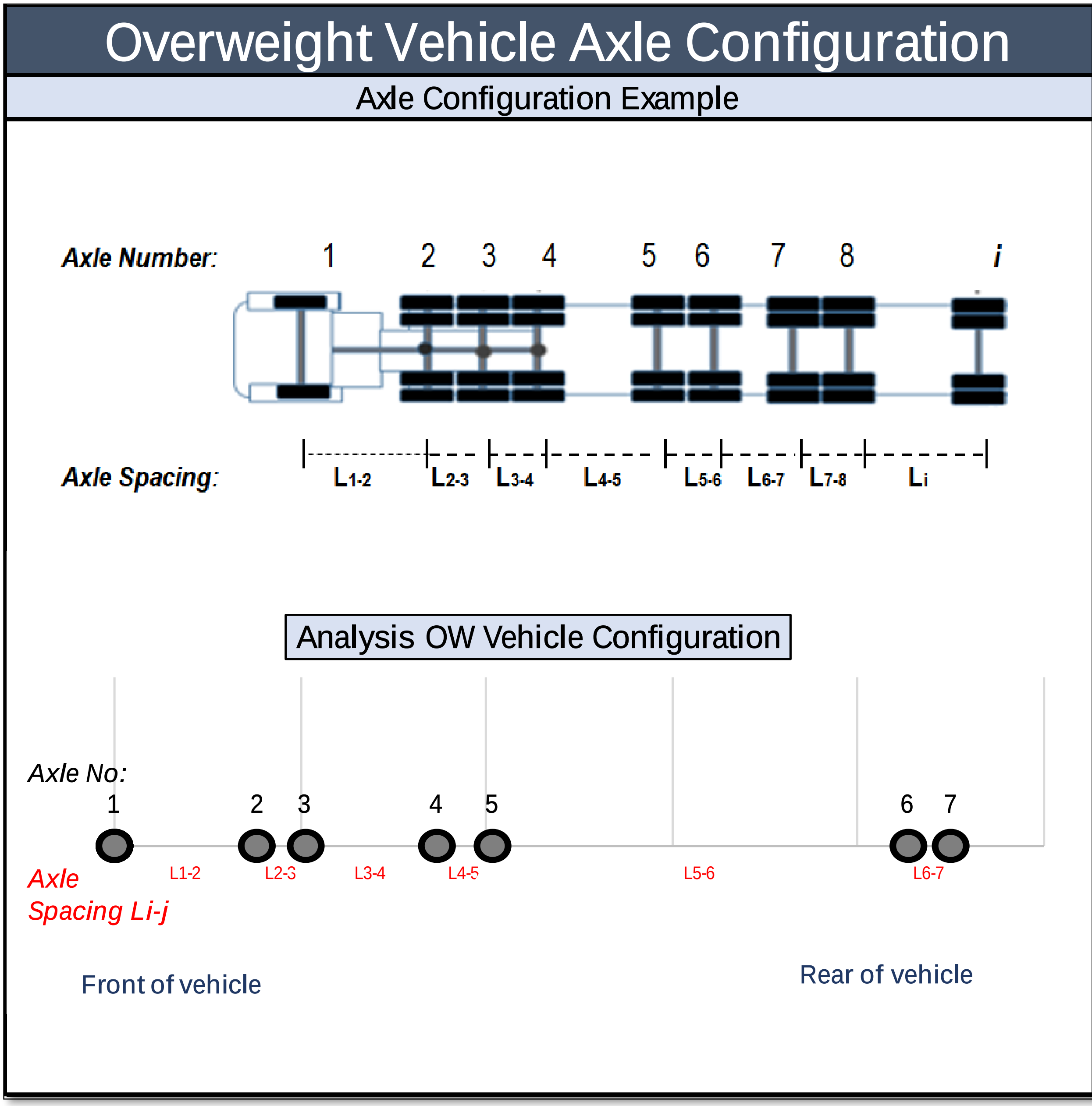


Figure 6.4. Overweight vehicle axle configuration schematic presented in panel No. two.

6.2 Output Information for Deterministic Analysis

6.2.1. PDAC Output Results

Output results based on AC permanent deformation and AC fatigue cracking are presented in Panel No. 3, *PDAC Results* within the main sheet. Figure 6.5 depicts PDAC results for single trip scenario in US dollar per lane-mile. As mentioned before, PDAC results are provided for the range of expected mid-depth AC temperatures. Output results for the user selected temperature are also provided in this panel. Figure 6.6 presents PDAC results for the entire move in US dollars. These results consider the PDAC values already presented in Figure 6.5, the number of lanes consumed, and the associated number of miles. PDACs at the user selected temperature for the entire trip are also provided. In the case example presented in Figure 6.5, permanent deformation-based and fatigue cracking-based PDAC values were determined to be 194.88 and 209.95 US dollars, respectively.

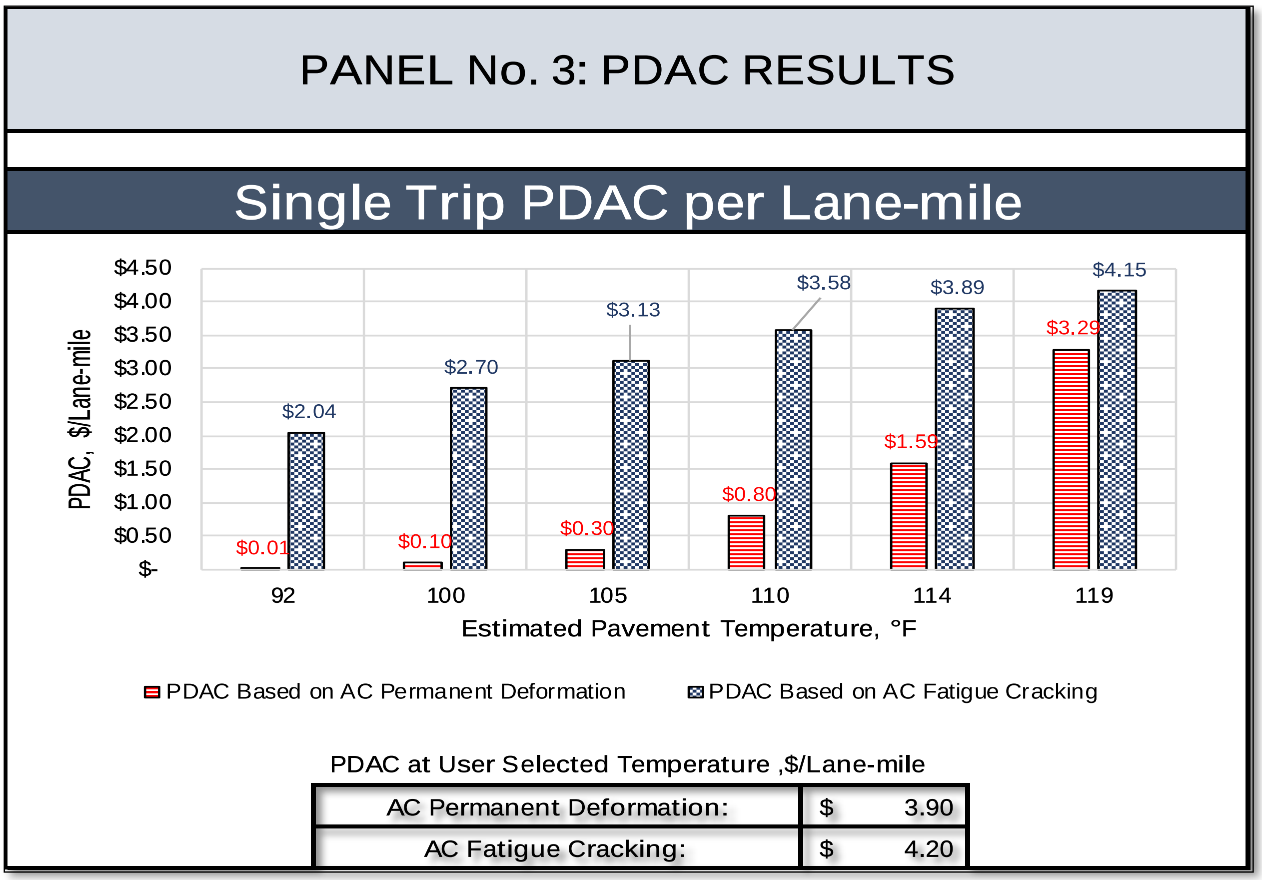


Figure 6.5. PDAC output results in US dollars per lane mile for a single trip scenario.

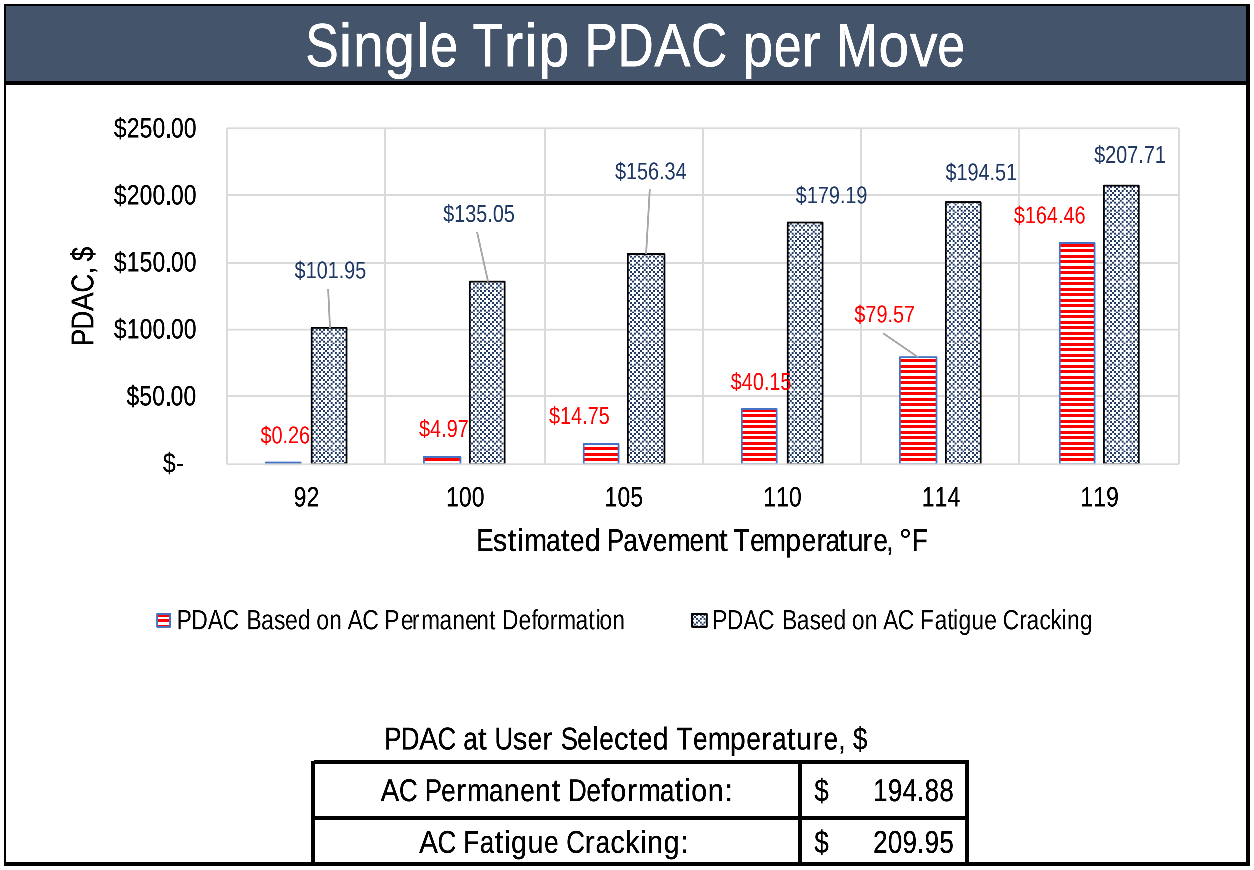


Figure 6.6. PDAC output results in US dollars for a single trip scenario.

6.2.2. LEF Output Results

LEFs represents pavement damage caused by a given axle group (single, tandem, tridem, or quad) compared to that caused by the reference 18,000 lb single-axle dual tires axle.
LEF calculations as presented in Section 2.3.2 are conducted in the package and presented as output results in panel No. 4, *Load Equivalency Factor Results*. Figure 6.7 presents AC permanent deformation-based LEF not only for the OW analysis vehicle, but also for the reference vehicle. Figure 6.8 provide the AC fatigue cracking-based LEFs. Results are again provided for the range of expected mid-depth AC temperatures and for the user selected temperature. Significantly high LEF values might trigger further evaluation. This type of analysis could quickly provide an indication of relative pavement damage before an OW permit is issued. In the case example described on Figure 6.7 and Figure 6.8 the fatigue cracking-based LEFs for the OW analysis vehicle were slightly higher than the permanent deformation-based LEFs. Also, while the permanent deformation-based LEFs were somehow constant with increasing temperature, the fatigue-cracking-based LEFs increased with increasing temperature.

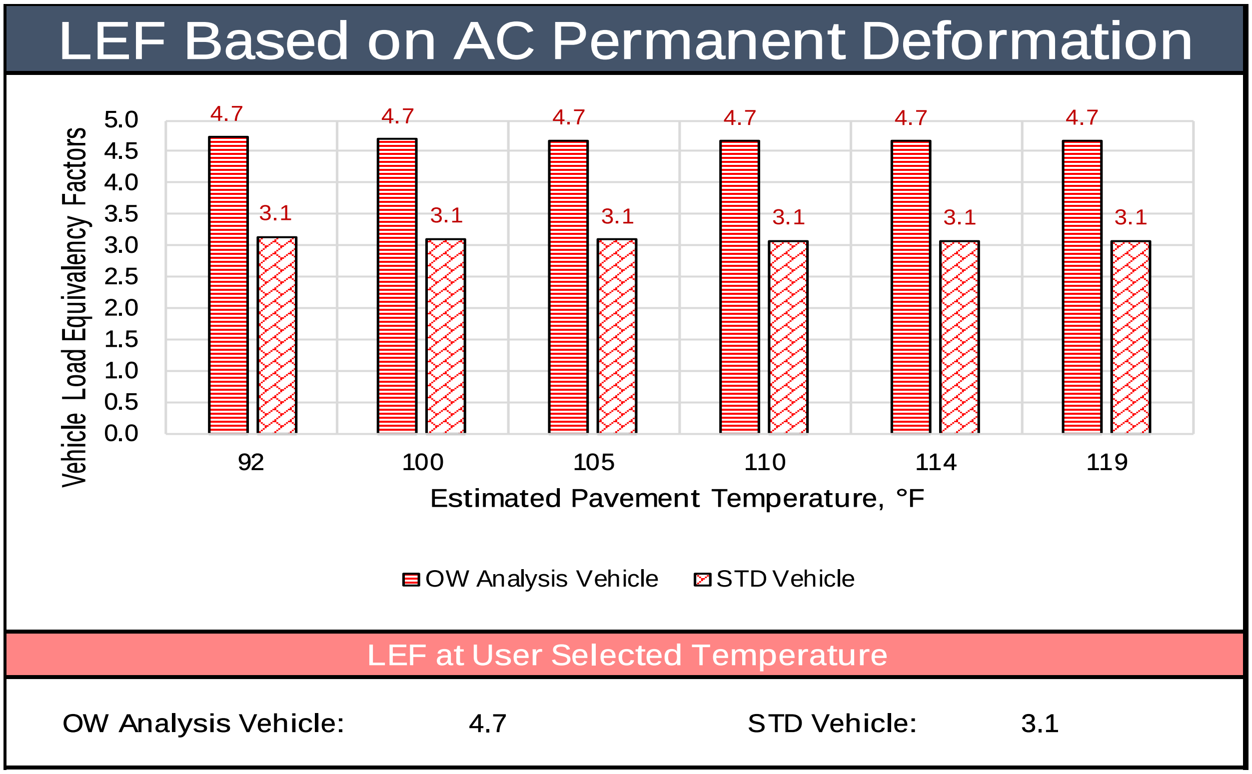


Figure 6.7. AC permanent deformation-based LEFs output result for single trip scenario.

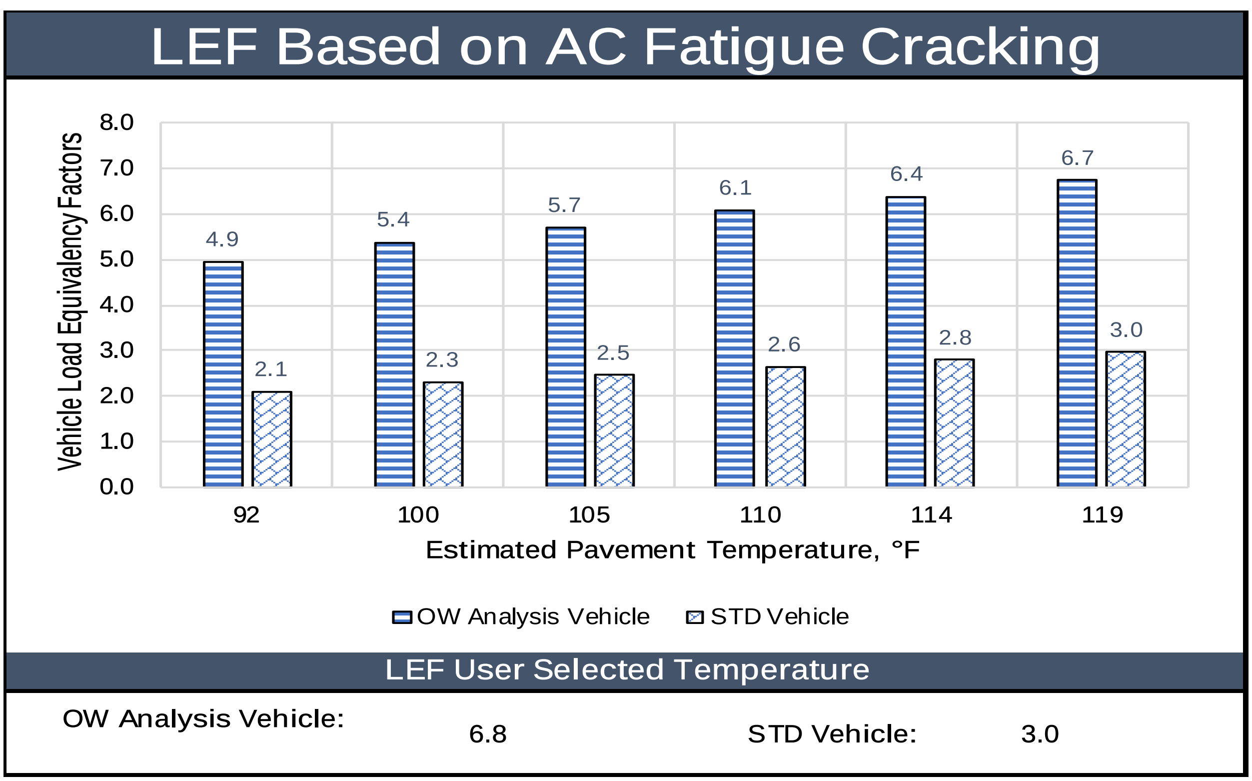


Figure 6.8. AC fatigue cracking-based LEFs output result for single trip scenario.

6.3 Input Information for Multi-Trip Analysis

The *Multi-Trip Analysis* sheet contains two panels, *Input* and *PDAC Multi-Trip Results*. Input information relative the probabilistic evaluation of OW vehicles is presented in this section. To carry out a probabilistic evaluation, the user needs to first input the climatic station in which the OW vehicle will mainly operate during the duration of the permit. In addition, the related miles traveled, and vehicle configuration information including, GVW, number of axles and vehicle width are necessary inputs.

6.3.1. Climatic Information

Table 6.4 summarizes the recommended inputs for the *climatic Stations* input panel. It should be noted that the climatic stations implemented in the multi-trip analysis are the same as those already presented in single-trip analysis (see Section 6.1.1). In the *Climatic Stations* panel, the user needs to select from a dropdown list one climatic station. The related miles traveled is also entered in this panel. As the probabilistic analysis presented in this section produce PDAC results in US dollars per lane mile, the user needs to estimate the *Related Miles Traveled* associated to all individual trips within the multi-trip permit. Figure 6.9 presents a screenshot of the panel where the user enters the requested values.

Table 6.4. Climatic Information and Related Miles Traveled Input Values for Multi-trip analysis.

Parameter	Design Input	Remarks
Climatic Station	Elko, Ely, Las Vegas, Lovelock, Mercury, Reno, South Tahoe, Tonopah, Winnemucca	User selects from dropdown list the climatic station that best represents the area in which the OW vehicle operates.
Related Miles Traveled	Number of miles associated to all trips during the duration of the multi-trip permit.	Value not currently available during the permit request process.

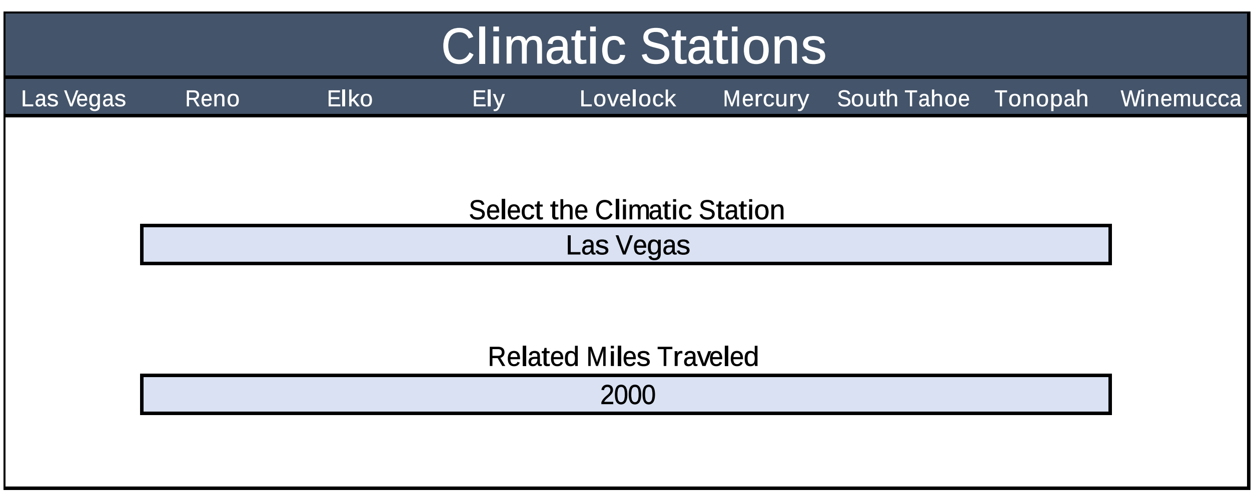


Figure 6.9. Climatic station input information for multi-trip analysis.

6.3.2. Overweight Vehicle Configuration

In the *Overweight Vehicle Configuration* input panel, the user enters information that characterizes the OW vehicle. This information is similar to that entered in the single-trip analysis, however, not as detailed. Table 6.5 shows the recommended input values for this panel. GVW, number of axles, and OW vehicle width are necessary inputs in the multi-trip analysis. Figure 6.10 shows a screenshot of the panel where the user enters the aforementioned values.

Table 6.5. Overweight Vehicle Configuration Input Values for Multi-trip analysis.

Parameter	Design Input	Remarks
Total Gross Vehicle Weight	Integer value in lb greater than zero.	Value directly obtained from over-dimensional permit form corresponding to GVW of OW vehicle as provided by trucking company.
Number of Axles in OW Vehicle	Integer value greater than zero.	Value directly obtained from over-dimensional permit form.
Overweight Vehicle Width	Integer value in feet greater than zero.	Value directly obtained from over-dimensional permit form.

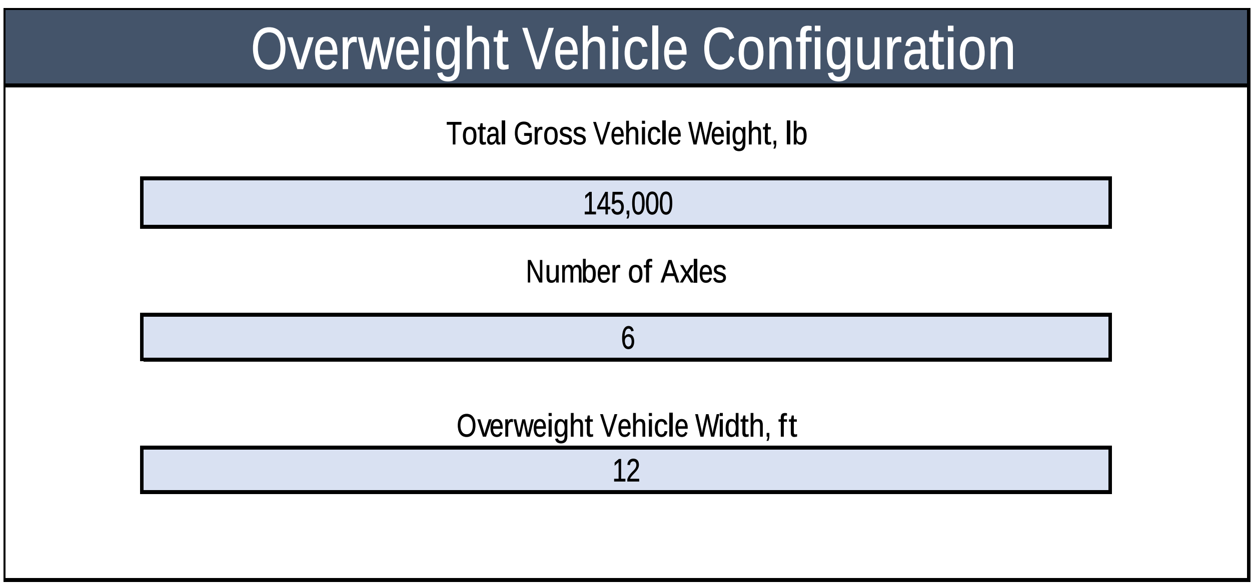


Figure 6.10. Overweight vehicle configuration input information for multi-trip analysis.

6.4 Output Information for Probabilistic Analysis

6.4.1. PDAC Output Results

Output results based on AC permanent deformation and AC fatigue cracking are provided for the multi-trip analysis. The probabilistic analysis produces distributions of PDAC values. Therefore, different percentiles of the corresponding distribution are provided for user selection. A cumulative percentile option is also provided for the user. This option consists of the average of five different percentiles (10^{th}, 30^{th}, 50^{th}, 70^{th}, and 90^{th}). Figure 6.11 depicts PDAC results for the multi-trip scenario in US dollars per lane-mile as presented in the package. In addition, Figure

6.12 presents total permanent deformation-based and fatigue cracking-based PDAC values. These values are calculated considering the related miles traveled and the width of the vehicle. It should be noted that the user is given the option to select the PDAC percentile among those presented in Figure 6.11. This option is selected from a dropdown list provided in the *Total Multi-Trip PDAC* output panel.

Multi-Trip PDAC, $/Lane-mile

AC Rutting-Based PDAC Values

Percentile:	10th	30th	50th	70th	90th	Cummulative
PDAC, $/Lane-mile:	0.01	0.02	0.07	0.33	1.79	0.44

AC Fatigue Cracking-Based PDAC Values

Percentile:	10th	30th	50th	70th	90th	Cummulative
PDAC, $/Lane-mile:	0.05	0.15	0.35	1.15	2.40	0.82

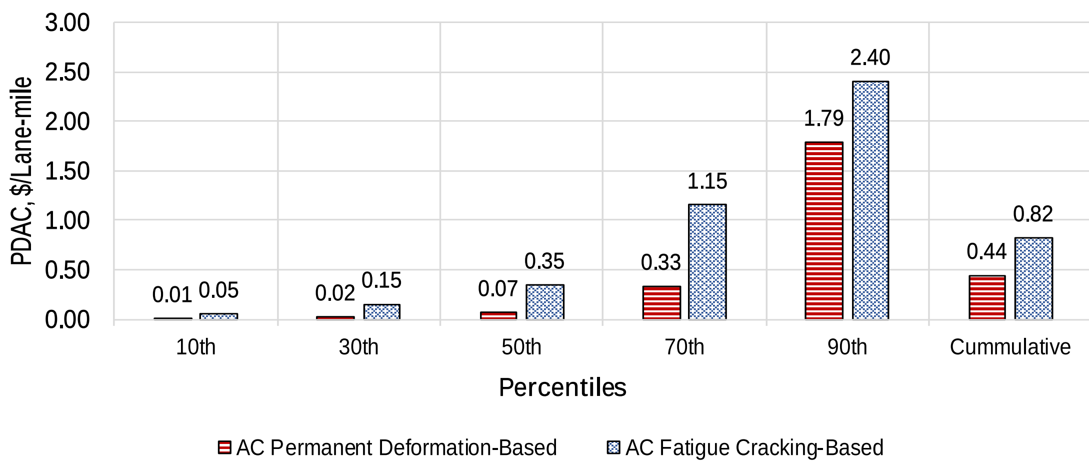


Figure 6.11. PDAC output results in US dollars per lane-mile for a multi-trip scenario.

Total Multi-Trip PDAC, $

Select Percentile	50th
Multi-trip PDAC Based on AC Permanent Deformation, $	135.43
Multi-trip PDAC Based on AC Fatigue Cracking, $	692.11

Figure 6.12. PDAC output results in US dollars a multi-trip scenario.

6.5 Default Information

As several parameters are used in the estimation of PDAC, some are not included as direct user inputs, but as default factors that can be updated or modified by the user in a different sheet (*Default Information*). Default parameters include: local calibration factors for AC performance models, AC mixture dynamic modulus fitting parameters, repair costs, default lane width, maximum axle spacing, reference vehicle, and reference or standard axle. A brief description of each parameter is given next.

6.5.1. Local Calibration Factors for AC Performance Models

The AC permanent deformation and AC fatigue cracking local calibration factors for NDOT Districts I, II, and III are provided as default values (refer to Table 2.4). It should be mentioned that during the PDAC calculation, these parameters are instantly updated as the user selects the NDOT district in which the OW vehicle will operate.

6.5.2. AC Mixture Dynamic Modulus Fitting Parameters

The Dynamic modulus fitting parameters are needed for estimating the stiffness of the AC mixture for fatigue cracking estimations. The necessary parameters to conduct the time-temperature shifting for the AC Dynamic modulus along with the fitting parameters are included in the default sheet. More information about these parameters can be found elsewhere else.[52]

6.5.3. Repair Costs

Repair costs of the different NDOT road categories in dollars per lane mile are provided. These values were already presented in Table 2.6. It should be noted that only values for road categories I, II, and III are implemented in the sheet and these values can be easily modified by the user.

6.5.4. Default Lane Width

The default lane width parameter directly impacts PDAC values. If the analysis OW vehicle has a width in feet greater than the default, the PDAC will have higher values as explained in Section 6.1.3. A default lane width of 12 feet is used in the package.

6.5.5. Maximum Axle Spacing

This parameter is used for axle grouping purposes. As explained in Section 6.1.3 this value is used to conduct the grouping of adjacent individual axles. An axle spacing of 60 inch is listed as maximum axle spacing to define the axle groups within the OW vehicle configuration. In other words, any individual axle or axles with axle spacing greater than the default value will be treated as an individual axle group.

6.5.6. Reference Vehicle

The reference vehicle used in PDAC calculation can be modified by the user. This is listed as a table in *Default Information* sheet. The user could modify the reference vehicle according to his needs. A typical 80,000 lb 18-wheel truck with one steering axle (12,000 lb) and two tandem axles (34,000 lb each) is listed as the default reference vehicle.

6.5.7. Standard Axle

The standard axle is used in the determination of LEFs. The default standard or reference axle configuration listed as the default is an 18,000 lb single axle with dual tires.

6.6 Summary

This chapter presented detailed information about the *Overweight Vehicle Analysis Package* – OVAP. The package can efficiently conduct pavement damage and PDAC analyses for OW vehicle trips. Information about the input and output results for both single-trip and multi-trip analyses was presented. Information about default parameters was also provided in this chapter. The pavement damage estimation conducted in the package rely on the determination of critical pavement responses that are instantaneously estimated from the embedded pavement responses database. Therefore, OVAP can determine LEFs and PDAC values for single and multi OW trip scenarios instantaneously.

CHAPTER 7 CASE STUDIES

To illustrate the PDAC analysis methodology, four different OW vehicle trips (three single-trip and one multi-trip) were evaluated in this chapter. The analyses were carried out using the *Overweight Vehicle Analysis Package* – OVAP. Input information was obtained from NDOT Over-dimensional permits. A comparative analysis is conducted between the PDAC attributable to a selected OW vehicle calculated using OVAP and the estimated permit fee for the same OW vehicle imposed by surrounding states. Also presented is a second comparative analysis between the estimated annual fees collected by NDOT in 2013 and those estimated using OVAP. In all cases, the reference vehicle employed in the PDAC calculation consisted of a 5-axle truck with 18 wheels and a GVW of 80,000 lb. The pavement repair costs listed in Table 2.6 were used in all case studies presented in this chapter. All analyses are assumed to happen on flexible pavements with excellent condition (i.e., RSL of 100).

7.1 Case Study I: Single Trip OW Vehicle with GVW 105,513 lb

Figure 7.1 presents the NDOT over-dimensional permit form for a single OW trip in January of 2014. The OW vehicle had a GVW of 105,513 lb. All necessary information to conduct the analysis can be directly copied or estimated from the permit form. For instance, VMT is estimated from the routing information. In this case, the OW vehicle move occurred in southern Nevada over Interstate 15 from the California/Nevada state line to the Nevada/Arizona state line with a total of 123 miles as shown in Figure 7.2. The width of the OW vehicle was 10 feet 6 inch which spanned over one lane only. Table 7.1 presents a summary of the input information.

NEVADA DOT

NEVADA DEPARTMENT OF TRANSPORTATION
1263 South Stewart Street, Carson City, Nevada 89712, 800-552-2127/775-888-7410
OVER-DIMENSIONAL VEHICLE PERMIT

Permit #
NDOT29750

Permit Type: TRIP - 5 DAY @ $25 GENERAL CREDIT CARD

Insurance: THE TRAVELERS INDEMNITY CO

COMBINED TRANSPORT INC
5656 CRATER LAKE AVENUE
CENTRAL POINT, OR, USA 97502

Route: **From:** CALIFORNIA/NEVADA LINE
To: NEVADA/ARIZONA LINE
Over Routes: I-15

Instructions:

Travel: FROM 1/2/2014 THRU 1/8/2014

Authorized: ☑ Weekend ☑ Night ☐ Holiday ☐ Workday Commute Hour

Description of Load: HAUL
LINK ESCAVATOR 201X3

Dimensions: **Width:** 10' 6" **Height:** Legal **Length:** Legal

Gross Weight: 105,513 **Total Axles:** 5 **Overhang:** **Front:** Legal **Rear:** Legal

Axle Spacing	1	16' 0"	2	4' 4"	3	38' 6"	4	4' 3"	5
Wheels	4		4		4		4		4
Wgt	12,500 (Steer weight)			46,550				46,463	

Figure 7.1. NDOT over-dimensional permit form for Case Study I.

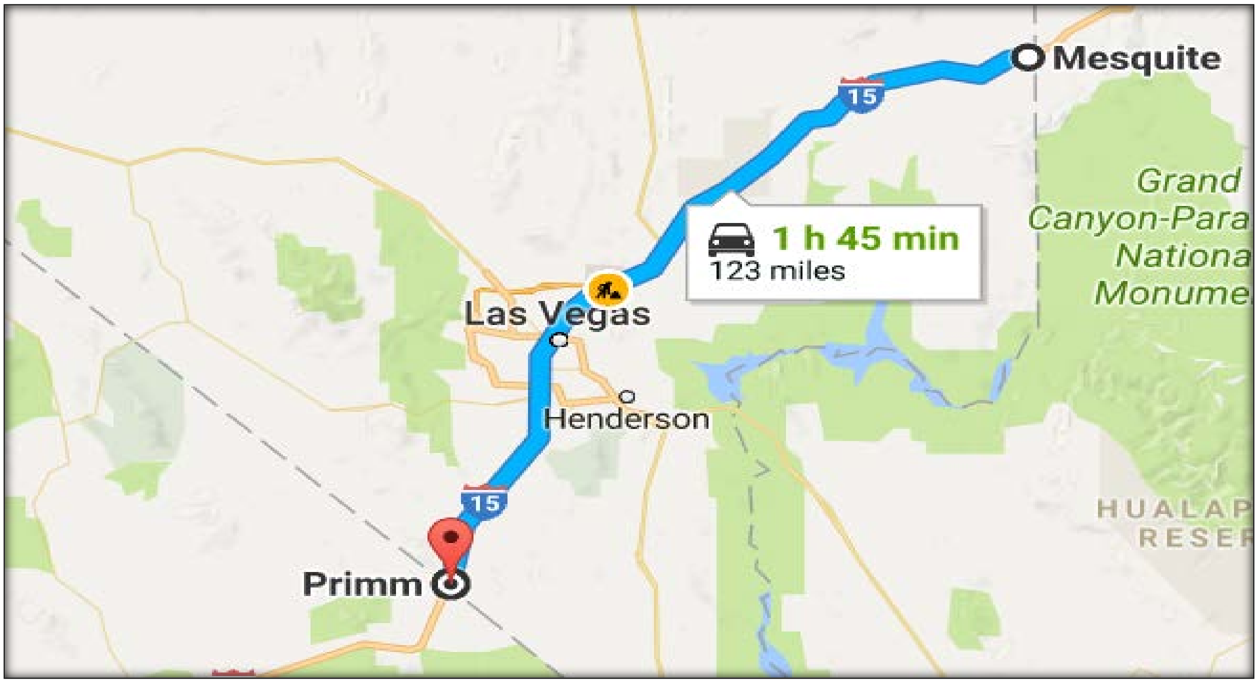


Figure 7.2. OW vehicle route for Case Study I.

Table 7.1. OW Vehicle Input Information for Case Study I.

<table>
<tr><th colspan="5">Climatic Information</th><th colspan="3">General Analysis Information</th></tr>
<tr><th colspan="3">Parameter</th><th colspan="2">Input</th><th colspan="2">Parameter</th><th>Input</th></tr>
<tr><td colspan="3">NDOT District</td><td colspan="2">I</td><td colspan="2">Operational Speed</td><td>55 mph</td></tr>
<tr><td colspan="3">Climatic Station</td><td colspan="2">Las Vegas</td><td colspan="2">VMT</td><td>123</td></tr>
<tr><td colspan="3" rowspan="2">Month of Move</td><td colspan="2" rowspan="2">January</td><td colspan="2">Pavement Structure</td><td>10 inch/10 CAB</td></tr>
<tr><td colspan="2">AADTT</td><td>5,000</td></tr>
<tr><th colspan="5">OW Vehicle Axle Configuration</th><th colspan="3" rowspan="4">Axle Grouping Table</th></tr>
<tr><td colspan="2">GVW, lb</td><td colspan="3">105,513</td></tr>
<tr><td colspan="2">Number of Axles</td><td colspan="3">5</td></tr>
<tr><td colspan="2">OW Vehicle Width, feet</td><td colspan="3">10.5</td></tr>
<tr><th>Axle No.</th><th>Designation</th><th>feet</th><th>inch</th><th>No. of Tires</th><th>Axle Group</th><th>Axle Group Load, lb</th><th>Widebase (Y/N)</th></tr>
<tr><td>1</td><td>$L_{1\text{-}2}$</td><td>16</td><td>0</td><td>2</td><td>1</td><td>12,500</td><td>N</td></tr>
<tr><td>2</td><td>$L_{2\text{-}3}$</td><td>4</td><td>4</td><td>4</td><td>2-3</td><td>46,550</td><td>N</td></tr>
<tr><td>3</td><td>$L_{3\text{-}4}$</td><td>38</td><td>6</td><td>4</td><td>4-5</td><td>46,463</td><td>N</td></tr>
<tr><td>4</td><td>$L_{4\text{-}5}$</td><td>4</td><td>3</td><td>4</td><td colspan="3" rowspan="2"></td></tr>
<tr><td>5</td><td>-</td><td></td><td></td><td>4</td></tr>
</table>

Figure 7.3 presents PDAC output results in US dollars per lane-mile for the anticipated pavement temperature range in January. The expected minimum and maximum pavement temperatures are 42 and 69°F, respectively. It is noted that the permanent deformation-based PDAC values attributable to OW movement were equal to zero during the evaluated period. On the other hand, fatigue cracking-based PDAC values varied with pavement temperature. Higher PDAC values for fatigue cracking were observed with increasing pavement temperatures from 42 to 69°F. Figure 7.4 presents PDAC values for the entire trip of 123 miles. The analysis OW vehicle only consumed one lane, thus, the total trip PDAC is directly obtained as the product of the PDAC

values presented in Figure 7.3 (in US dollars per lane mile) and VMT. PDAC values between 8.76 and 19.05 US dollars per trip were determined for the evaluated time period.

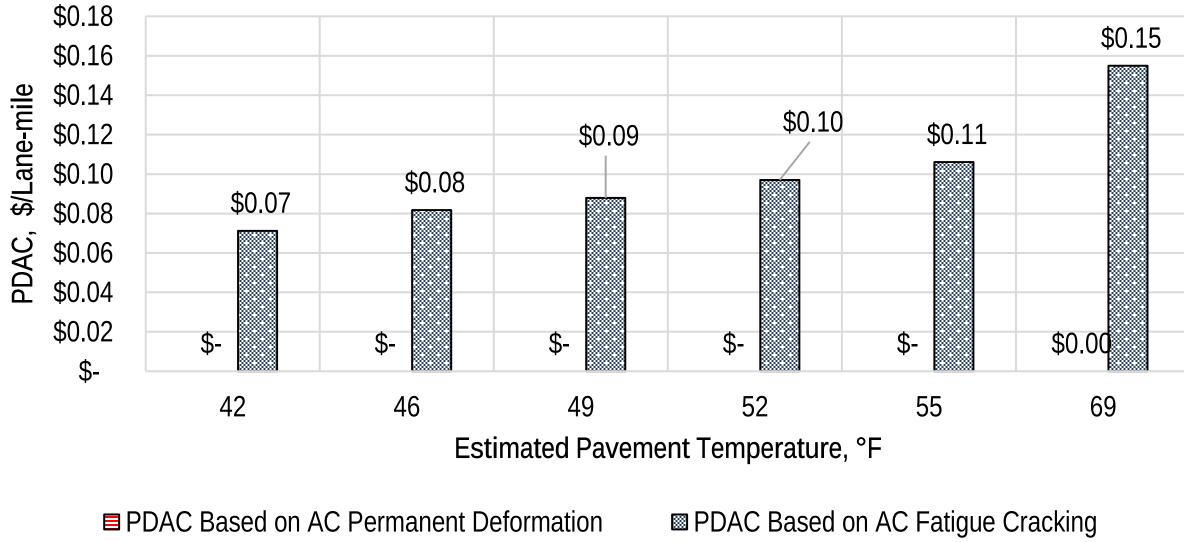


Figure 7.3. OW vehicle PDAC values in US dollars per lane mile for Case study I.

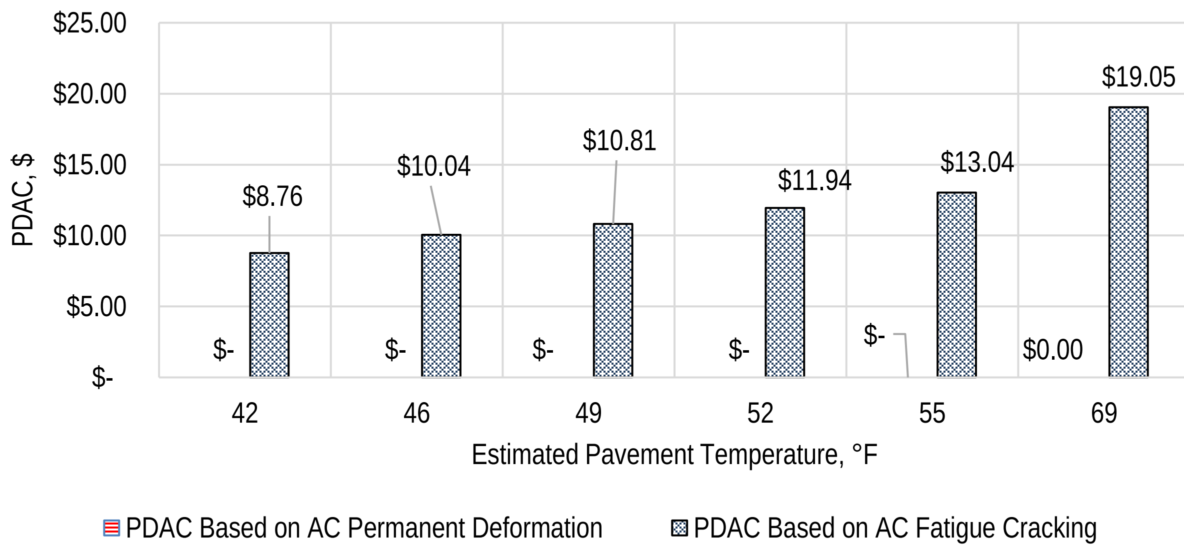
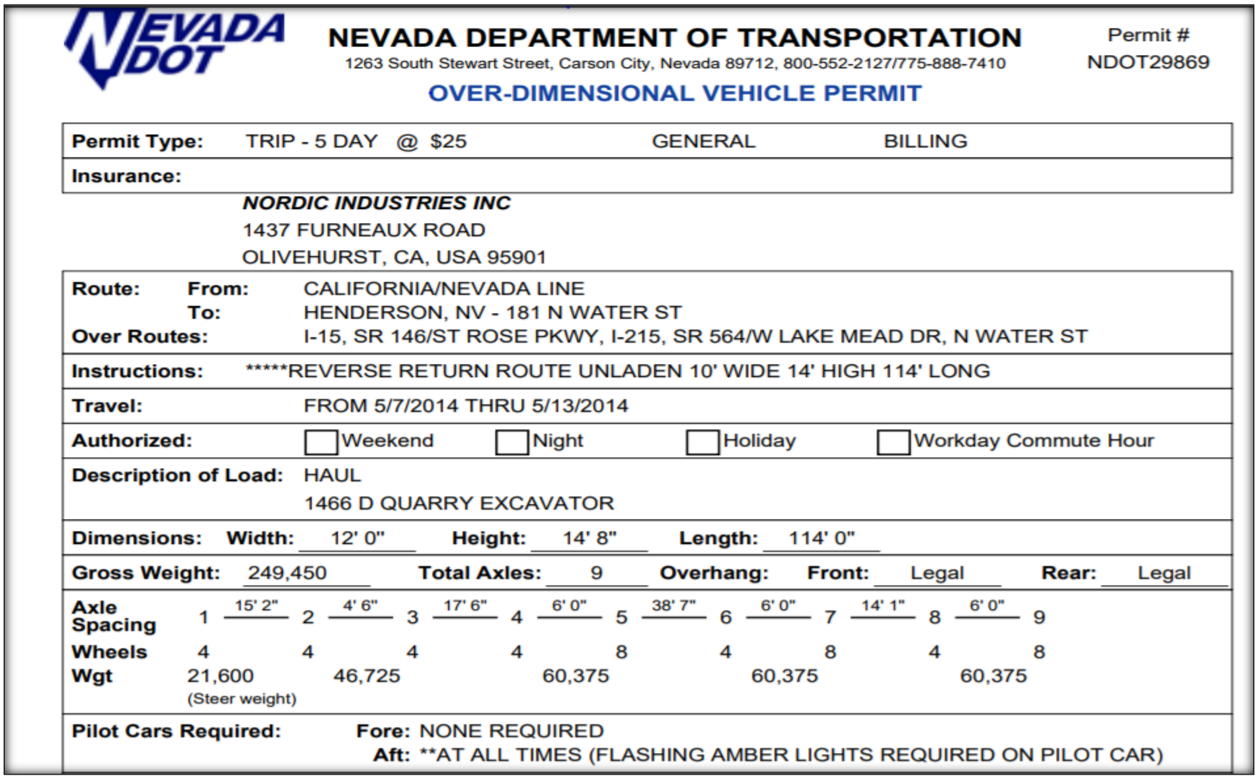


Figure 7.4. OW vehicle PDAC values in US dollars per trip for Case study I.

7.2 Case Study II: Single Trip OW Vehicle with GVW 249,450 lb

Figure 7.5 presents the NDOT over-dimensional permit form for a single OW trip in May of 2014. The OW vehicle had a GVW of 249,450 lb. The OW vehicle move occurred in southern Nevada from the California/Nevada state line to Henderson, Nevada with a total of 40.8 miles as shown in Figure 7.6. The vehicle traveled over three major highway sections: Interstate 15, SR 146, and Interstate 215. Therefore, the PDAC analysis was conducted over the three sections individually. The width of the OW vehicle was 12 feet which consumed only one lane. Table 7.2 presents a summary of the input information. An operational speed of 45 mph was used due the higher GVW of the OW analysis vehicle. It should be noted that different VMT values, pavement structures, and AADTT values were used in this analysis corresponding to the three different roadway sections.



NEVADA DOT

NEVADA DEPARTMENT OF TRANSPORTATION
1263 South Stewart Street, Carson City, Nevada 89712, 800-552-2127/775-888-7410
OVER-DIMENSIONAL VEHICLE PERMIT

Permit #
NDOT29869

Permit Type: TRIP - 5 DAY @ $25 GENERAL BILLING

Insurance:

NORDIC INDUSTRIES INC
1437 FURNEAUX ROAD
OLIVEHURST, CA, USA 95901

Route: **From:** CALIFORNIA/NEVADA LINE
To: HENDERSON, NV - 181 N WATER ST
Over Routes: I-15, SR 146/ST ROSE PKWY, I-215, SR 564/W LAKE MEAD DR, N WATER ST

Instructions: *****REVERSE RETURN ROUTE UNLADEN 10' WIDE 14' HIGH 114' LONG

Travel: FROM 5/7/2014 THRU 5/13/2014

Authorized: ☐ Weekend ☐ Night ☐ Holiday ☐ Workday Commute Hour

Description of Load: HAUL
1466 D QUARRY EXCAVATOR

Dimensions: **Width:** 12' 0" **Height:** 14' 8" **Length:** 114' 0"

Gross Weight: 249,450 **Total Axles:** 9 **Overhang:** **Front:** Legal **Rear:** Legal

Axle Spacing: 1 —15' 2"— 2 —4' 6"— 3 —17' 6"— 4 —6' 0"— 5 —38' 7"— 6 —6' 0"— 7 —14' 1"— 8 —6' 0"— 9

Wheels: 4 4 4 4 8 4 8 4 8

Wgt: 21,600 (Steer weight) 46,725 60,375 60,375 60,375

Pilot Cars Required: **Fore:** NONE REQUIRED
Aft: **AT ALL TIMES (FLASHING AMBER LIGHTS REQUIRED ON PILOT CAR)

Figure 7.5. NDOT over-dimensional permit form for Case Study II.

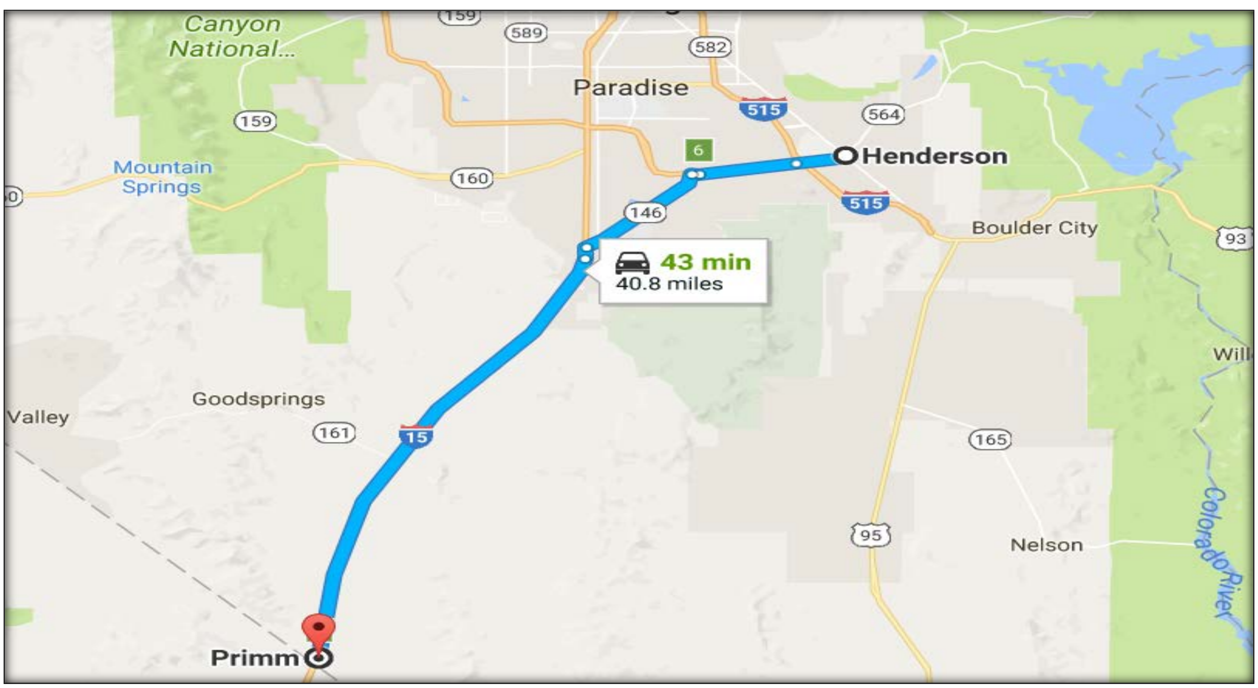


Figure 7.6. OW vehicle route for Case Study II.

Table 7.2. OW Vehicle Input Information for Case Study II.

Climatic Information		General Analysis Information	
Parameter	***Input***	***Parameter***	***Input***
NDOT District	I	*Operational Speed*	45 mph
Climatic Station	Las Vegas	*VMT*	**I15**:28.0, **SR146**:6.8, **I215**:6.0
Month of Move	May	*Pavement Structures*	**I-15**:10 inch/10 CAB
			SR146:8 inch/8 CAB
OW Vehicle Axle Configuration			**I-215**:8 inch/10 CAB
GVW, lb	249,450	*AADTT*	**I15**:5,000; **SR146**: 1,200; **I215**: 2,500
Number of Axles	9		
OW Vehicle Width, feet	12	**Axle Grouping Table**	

Axle No.	Designation	feet	inch	No. of Tires
1	L_{1-2}	15	2	2
2	L_{2-3}	4	6	4
3	L_{3-4}	17	6	4
4	L_{4-5}	6	0	4
5	L_{5-6}	38	7	4
6	L_{6-7}	6	0	4
7	L_{7-8}	14	1	4
8	L_{8-9}	6	0	4
9	-			4

Axle Group	Axle Group Load, lb	Widebase (Y/N)
1	21,600	N
2-3	46,725	N
4-5	60,375	N
6-7	60,375	N
8-9	60,375	N

Figure 7.7 presents PDAC output results in US dollars per lane-mile for the Interstate 15 section (VMT of 28 miles). It is noted that permanent deformation-based PDAC values attributable to the OW movement are significantly lower than the fatigue cracking-based PDAC. Figure 7.8 presents the estimated PDAC values in US dollars for the trip within this section. The OW vehicle move resulted in minimum and maximum PDAC values of 41.45 and 151.75 US dollars, respectively.

Similarly, Figure 7.9 presents PDAC output results in US dollars per lane-mile for the SR 146 section (VMT of 6.8 miles). Both Permanent deformation-based and fatigue cracking-based PDAC values attributable to OW movement were significantly higher than those presented in Figure 7.7. Thus, suggesting that PDAC values are significantly impacted by pavement structure. Figure 7.10 presents the estimated PDAC values attributable to the OW vehicle move for the trip within this section. The OW vehicle move resulted in minimum and maximum PDAC values of 32.59 and 128.53 US dollars, respectively.

Figure 7.11 presents PDAC output results in US dollars per lane-mile for the Interstate I-215 section (VMT of 6.0 miles). In this case PDAC values attributable to OW movement were slightly lower than those determined for SR 146 section. Figure 7.12 presents the determined PDAC values for trip within this section. Minimum and maximum PDAC values of 25.78 and 83.81 US dollars were determined, respectively.

Table 7.3 summarizes permanent deformation-based and fatigue cracking-based PDAC values attributable to the OW movement for the three sections considered in the analysis. The total trip PDAC was determined as the summation of the respective sections' PDAC values. It is noted that fatigue cracking-based PDAC values were significantly higher than the permanent deformation-based PDAC values with maximum values of 364.1 and 47.7 US dollars, respectively. The PDAC attributable to the OW vehicle move analyzed ranged between 99.8 and 364.1 US dollars.

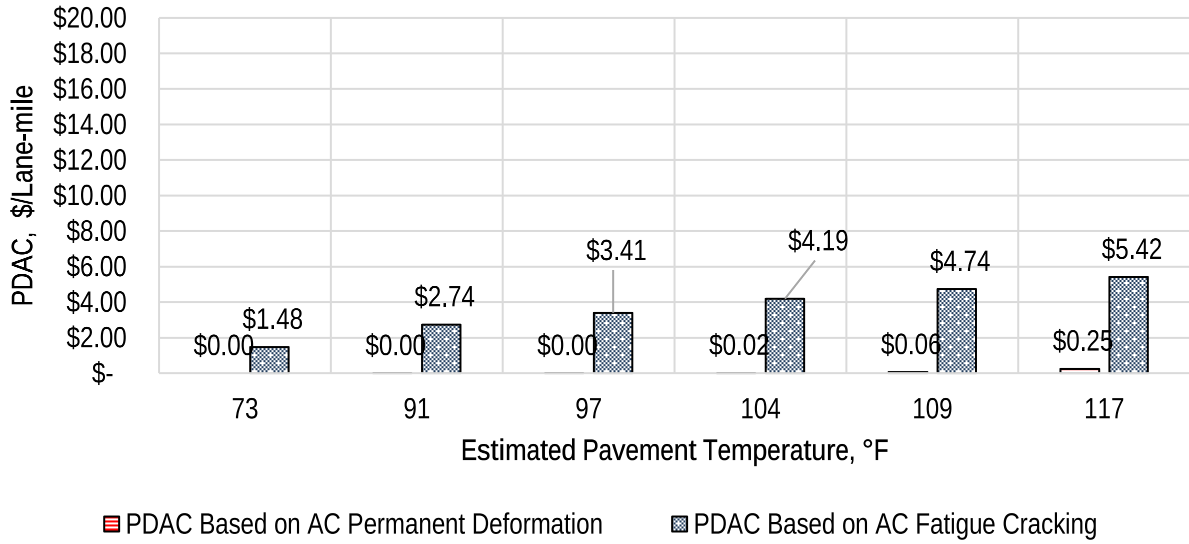


Figure 7.7. OW vehicle PDAC values in US dollars per lane mile for Case study II (Interstate 15 Section).

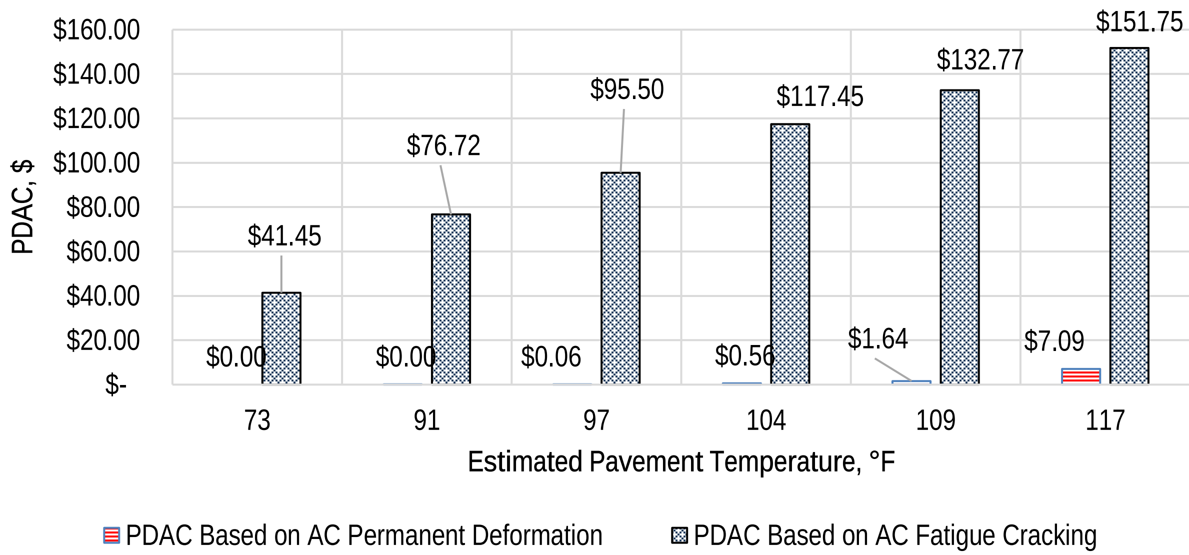


Figure 7.8. OW vehicle PDAC values in US dollars per trip for Case study II (Interstate 15 Section).

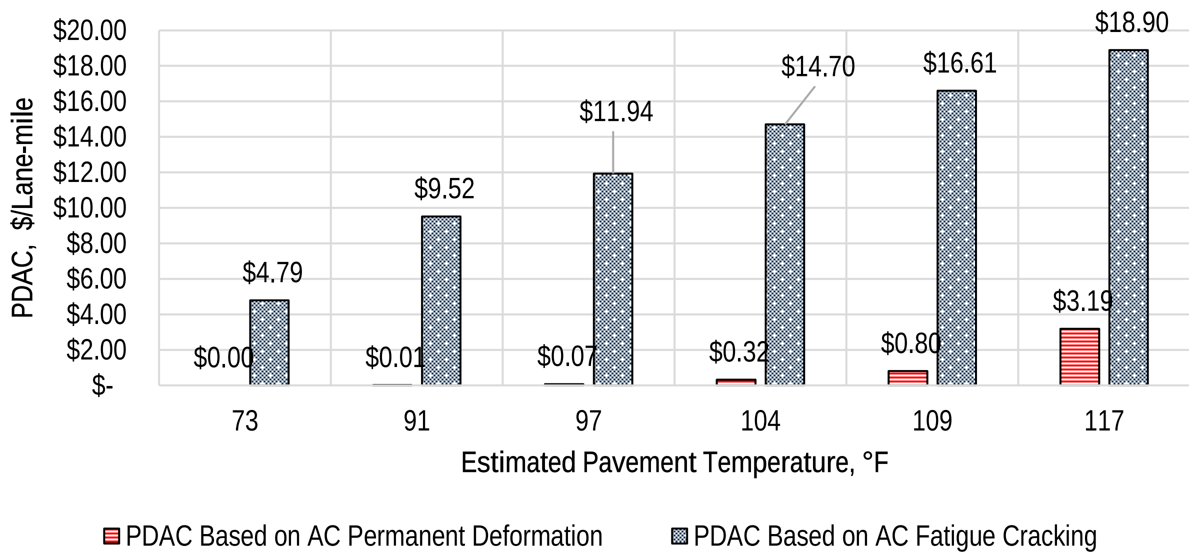


Figure 7.9. OW vehicle PDAC values in US dollars per lane mile for Case study II (SR 146 Section).

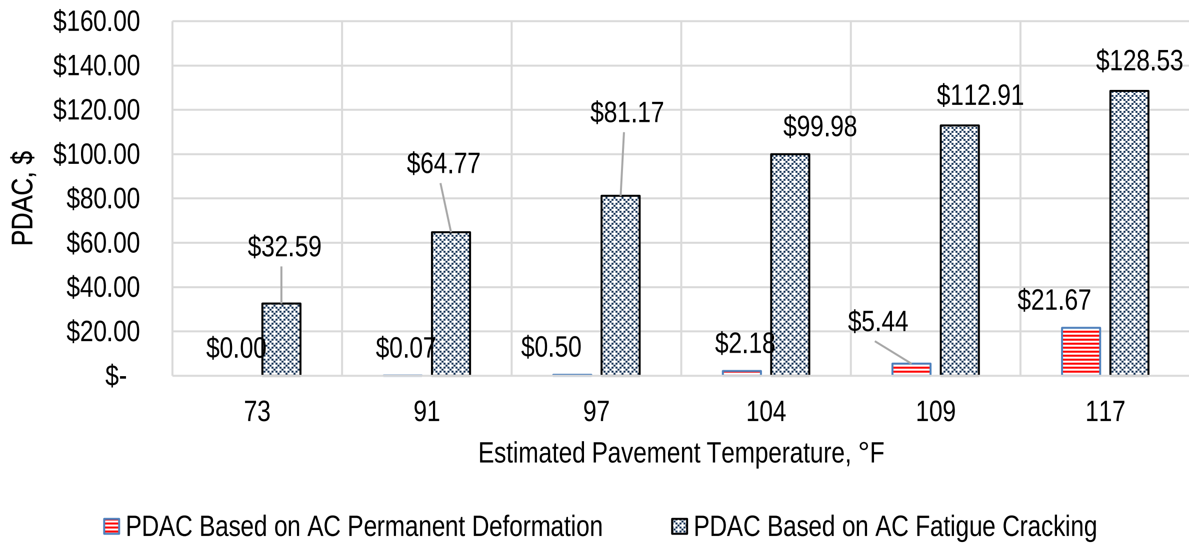


Figure 7.10. OW vehicle PDAC values in US dollars per trip for Case study II (SR 146 Section).

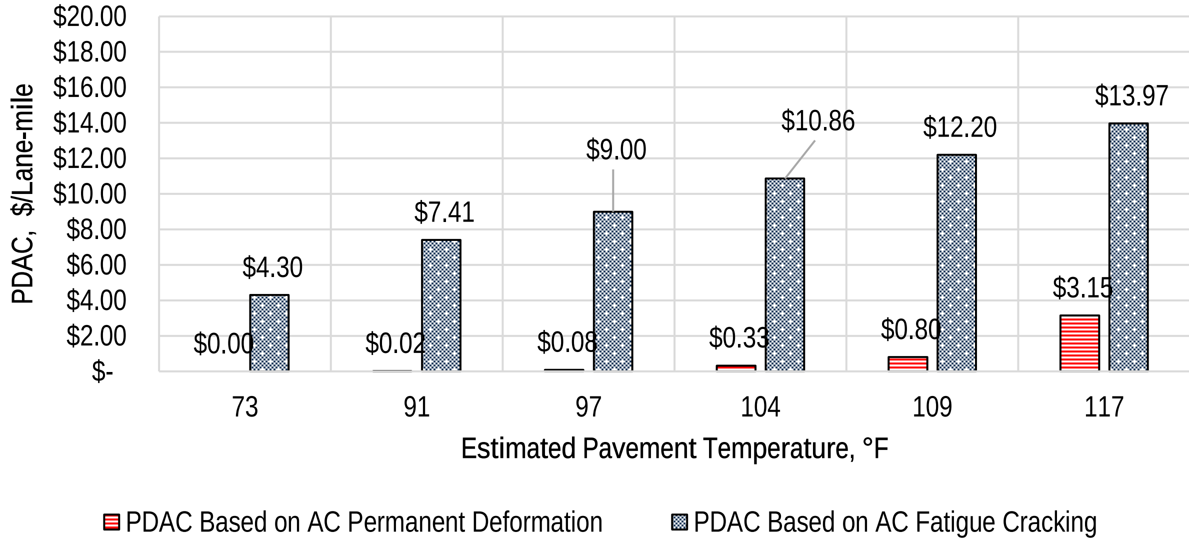


Figure 7.11. OW vehicle PDAC values in US dollars per lane mile for Case study II (Interstate 215 Section).

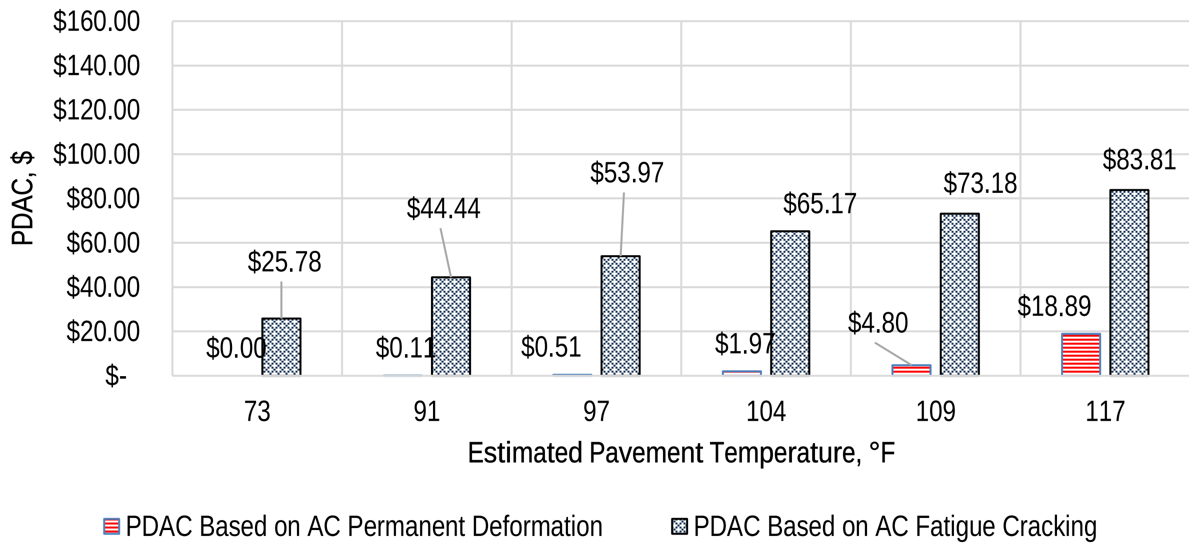


Figure 7.12. OW vehicle PDAC values in US dollars per trip for Case study II (Interstate 215 Section).

Table 7.3. Summary of Total Trip PDAC Values in US Dollars for Case Study II.

Pavement Temperature, °F	Distress Type	Route Sections			
		Interstate 15	SR 146	Interstate 215	Total Trip
73	AC Permanent Deformation	$0.0	$0.0	$0.0	$0.0
	AC Fatigue Cracking	$41.4	$32.6	$25.8	$99.8
91	AC Permanent Deformation	$0.0	$0.1	$0.1	$0.2
	AC Fatigue Cracking	$76.7	$64.8	$44.4	$185.9
97	AC Permanent Deformation	$0.1	$0.5	$0.5	$1.1
	AC Fatigue Cracking	$95.5	$81.2	$54.0	$230.6
104	AC Permanent Deformation	$0.6	$2.2	$2.0	$4.7
	AC Fatigue Cracking	$117.5	$100.0	$65.2	$282.6
109	AC Permanent Deformation	$1.6	$5.4	$4.8	$11.9
	AC Fatigue Cracking	$132.8	$112.9	$73.2	$318.9
117	AC Permanent Deformation	$7.1	$21.7	$18.9	$47.7
	AC Fatigue Cracking	$151.8	$128.5	$83.8	$364.1

7.3 Case Study III: Single Trip OW Vehicle with GVW 500,500 lb

Figure 7.13 presents the NDOT over-dimensional permit form for a single OW trip in March of 2014. The OW vehicle had a GVW of 500,500 lb. The OW vehicle move occurred in northern Nevada over US 50 route from the Utah/Nevada state line to Ely, Nevada with a total of 64 miles as shown in Figure 7.14. The width of the OW vehicle was 21 feet 2 inch which spanned over two lanes. Table 7.4 presents a summary of the input information. An operational speed of 35 mph was estimated due to the higher GVW of the analysis OW vehicle.

NEVADA DEPARTMENT OF TRANSPORTATION
1263 South Stewart Street, Carson City, Nevada 89712, 800-552-2127/775-888-7410
OVER-DIMENSIONAL VEHICLE PERMIT

Permit #
NDOT36584

Permit Type:	TRIP - 5 DAY @ $25	GENERAL	CREDIT CARD
Insurance:			

PERKINS SPECIALIZED TRANSPORTATION CONTRACTING
1800 RIVERVIEW DRIVE
NORTHFIELD, MN, USA 55051

Route: **From:** UTAH/NEVADA LINE
To: ELY NV
Over Routes: US 6/50, US 6

Instructions: ****PERMITTEE TO USE CLEARANCE POLE TO CHECK HEIGHT. PERMITTEE RESPONSIBLE FOR CLEARING ALL STRUCTURES, UTILITY LINES AND SIGNALS; **NEVADA HIGHWAY PATROL ESCORT REQUIRED AND PLACEMENT OF UNITS LEFT TO THE DISCRETION OF NHP **PERMITTEE HAS COMPLETED A ROUTE SURVEY--NEEDS COPY WITH PERMIT

Travel: FROM 3/17/2014 THRU 3/21/2014

Authorized: ☐ Weekend ☐ Night ☐ Holiday ☐ Workday Commute Hour

Description of Load: HAUL
BOILER

Dimensions: **Width:** 21' 2" **Height:** 17' 3" **Length:** 222' 7"

Gross Weight: 500,500 **Total Axles:** 16 **Overhang:** **Front:** Legal **Rear:** Legal

Axle Spacing	1	19' 2"	2	5' 0"	3	17' 8"	4	5' 9"	5	12' 4"	6	5' 9"	7	67' 9"	8	5' 9"	9	12' 4"	10
Wheels	4		4		4		4		4		4		4		4		4		4
Wgt	20,000 (Steer weight)			47,500				76,500				76,500				73,000			

Axle Spacing	10	5' 9"	11	12' 5"	12	5' 9"	13	15' 8"	14	18' 0"	15	5' 0"	16
Wheels	4		4		4		4		4		4		4
Wgt		73,000 (Steer weight)				73,000				19,000		42,000	

Figure 7.13. NDOT over-dimensional permit form for Case Study III.

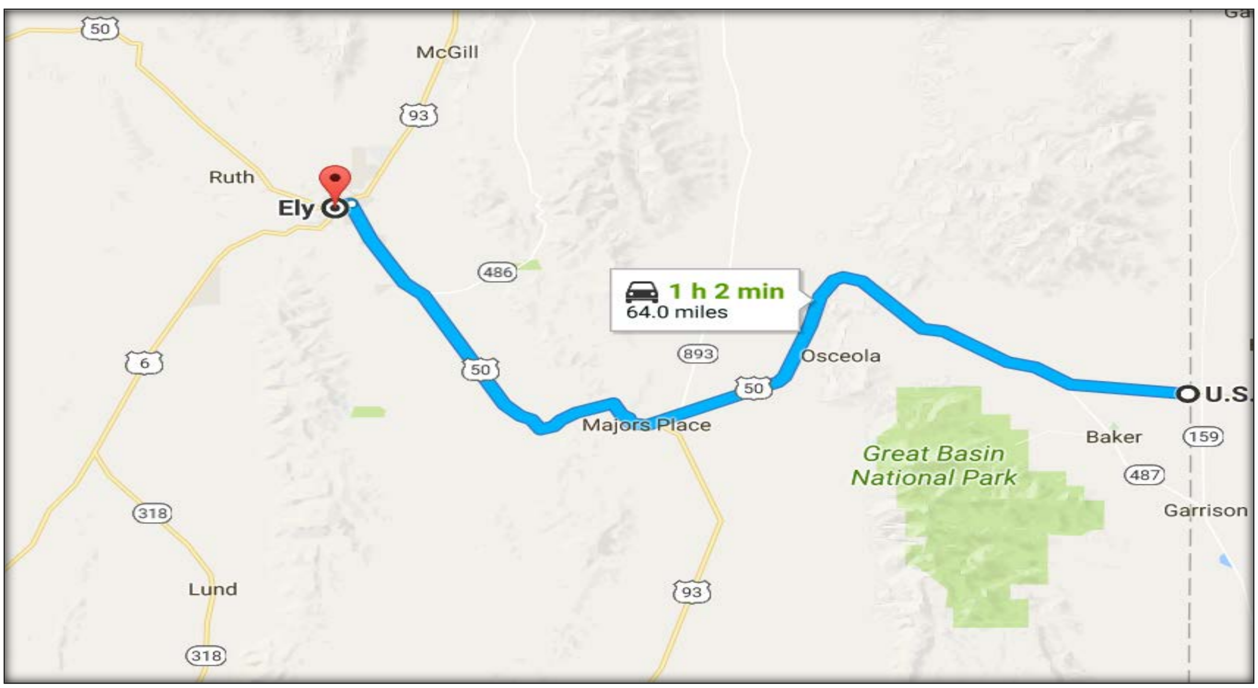


Figure 7.14. OW vehicle route for Case Study III.

Table 7.4. OW Vehicle Input Information for Case Study III.

Climatic Information		General Analysis Information	
Parameter	***Input***	***Parameter***	***Input***
NDOT District	III	*Operational Speed*	35 mph
Climatic Station	Ely	*VMT*	64
Month of Move	July	*Pavement Structure*	8 inch/10 CAB
		AADTT	400

OW Vehicle Axle Configuration	
GVW, lb	500,500
Number of Axles	16
OW Vehicle Width, feet	21.2

Axle No.	Designation	feet	inch	No. of Tires
1	L_{1-2}	19	2	2
2	L_{2-3}	5	0	4
3	L_{3-4}	17	8	4
4	L_{4-5}	5	9	4
5	L_{5-6}	12	4	4
6	L_{6-7}	5	9	4
7	L_{7-8}	67	9	4
8	L_{8-9}	5	9	4
9	L_{9-10}	12	4	4
10	L_{10-11}	5	9	4
11	L_{11-12}	12	5	4
12	L_{12-13}	5	9	4
13	L_{13-14}	15	8	4
14	L_{14-15}	18	0	4
15	L_{15-16}	5	0	4
16				4

Axle Grouping Table

Axle Group	Axle Group Load, lb	Widebase (Y/N)
1	20,000	N
2-3	47,500	N
4-5	76,500	N
6-7	76,500	N
8-9	73,000	N
10-11	73,000	N
12-13	73,000	N
14	19,000	N
15-16	42,000	N

Figure 7.15 presents PDAC output results in US dollars per lane-mile for the anticipated pavement temperature range in March. The expected minimum and maximum pavement temperatures are 65 and 99°F, respectively. Significantly high fatigue cracking-based PDAC values were observed for the entire range of pavement temperatures. On the other hand, permanent deformation-based PDAC values increased exponentially with increasing temperature. Figure 7.16 presents PDAC values for the entire trip of 64 miles. The analysis OW vehicle consumed two lanes. PDAC values between 2,674.57 and 2,948.10 US dollars per trip were determined for the evaluated time period.

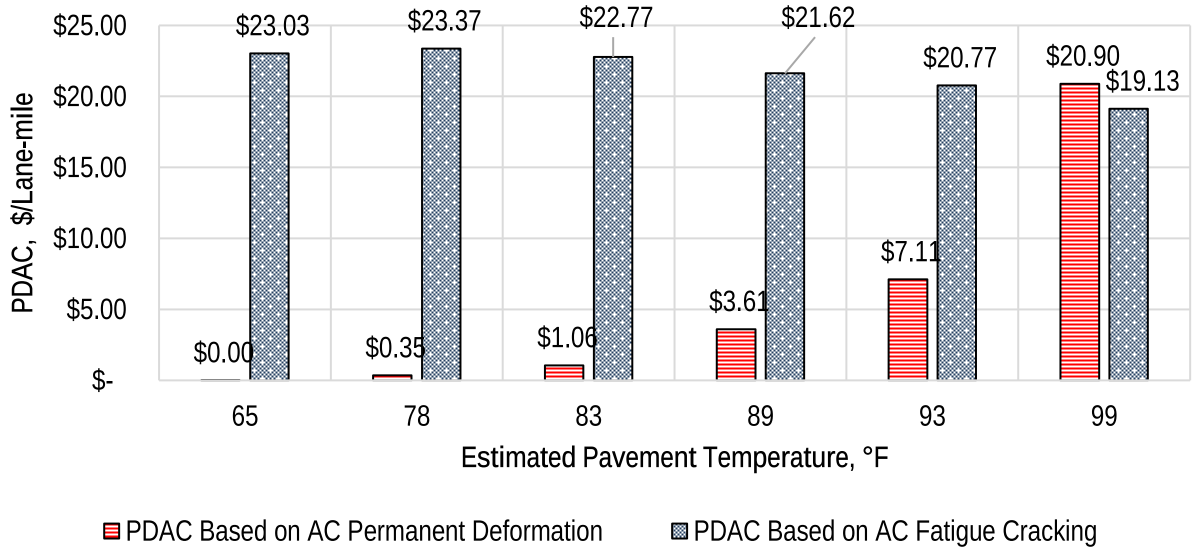


Figure 7.15. OW vehicle PDAC values in US dollars per lane mile for Case Study III.

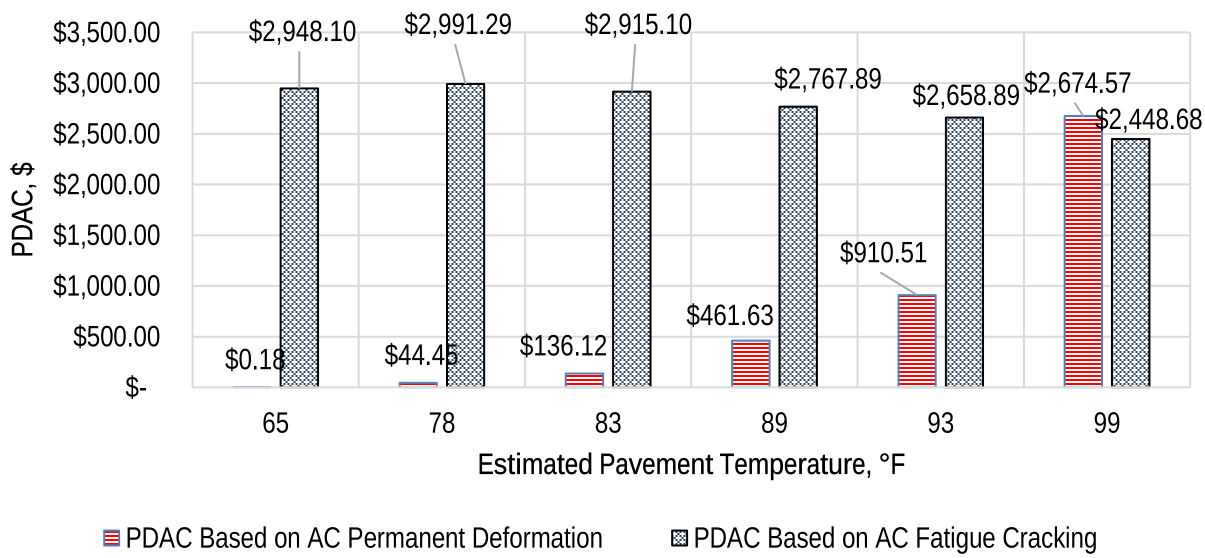
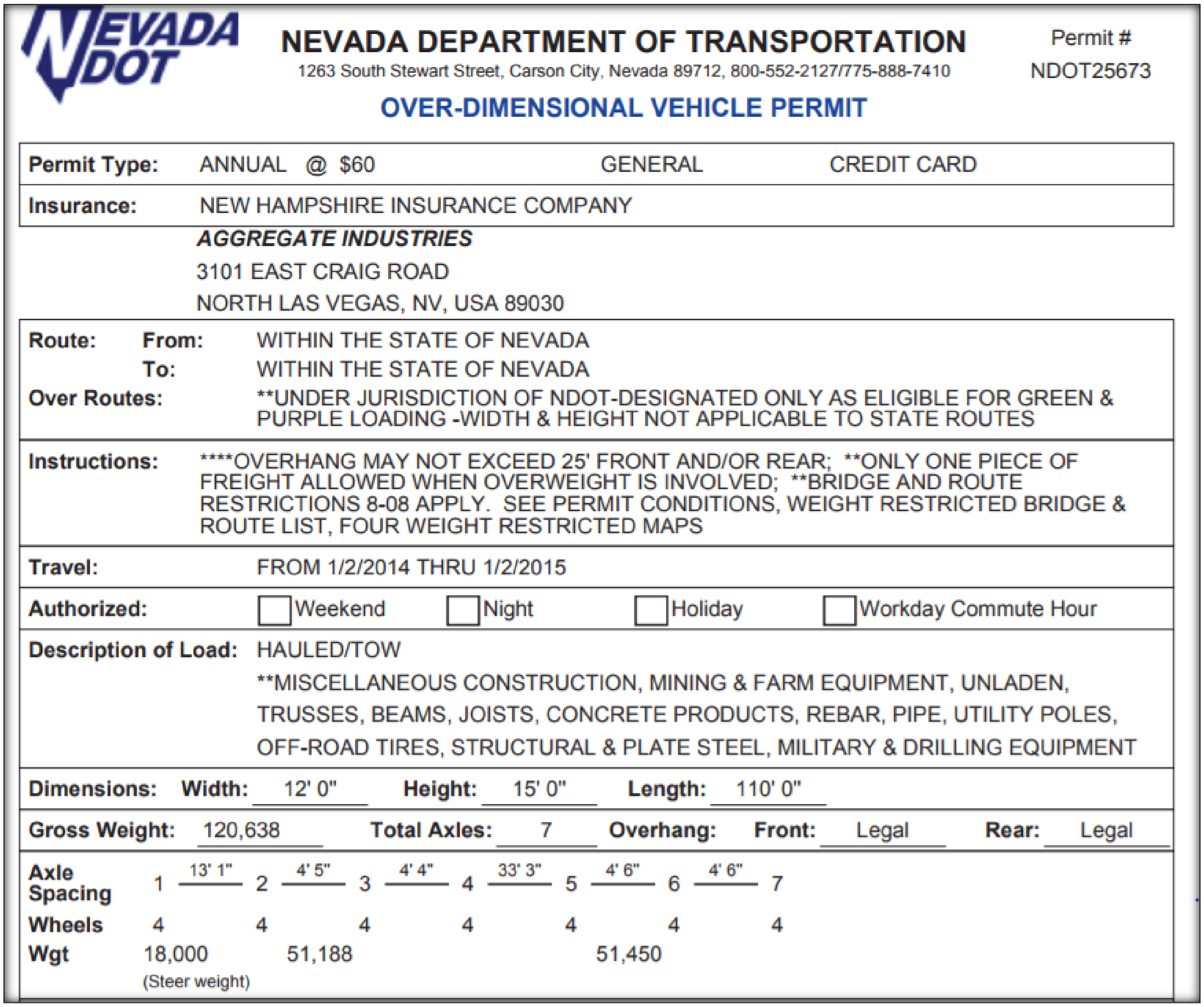


Figure 7.16. OW vehicle PDAC values in US dollars per trip for Case Study III.

7.4 Case Study IV: Multi-Trip OW Vehicle with GVW 120,638 lb

Figure 7.17 presents the NDOT over-dimensional permit form for a multi OW trip in year 2015. The OW vehicle had a GVW of 120,638 lb. The width of the OW vehicle was 12 feet. Table 7.5 presents the necessary input information needed to determine PDAC attributable to this OW vehicle. The probabilistic analysis approach was used to estimate the PDAC distribution. The OW vehicle is assumed to travel 2,500 miles a year. The Reno weather station was used in this evaluation.



NEVADA DOT

NEVADA DEPARTMENT OF TRANSPORTATION
1263 South Stewart Street, Carson City, Nevada 89712, 800-552-2127/775-888-7410

Permit #
NDOT25673

OVER-DIMENSIONAL VEHICLE PERMIT

Permit Type:	ANNUAL @ $60	GENERAL	CREDIT CARD
Insurance:	NEW HAMPSHIRE INSURANCE COMPANY		

AGGREGATE INDUSTRIES
3101 EAST CRAIG ROAD
NORTH LAS VEGAS, NV, USA 89030

Route: From: WITHIN THE STATE OF NEVADA
To: WITHIN THE STATE OF NEVADA
Over Routes: **UNDER JURISDICTION OF NDOT-DESIGNATED ONLY AS ELIGIBLE FOR GREEN & PURPLE LOADING -WIDTH & HEIGHT NOT APPLICABLE TO STATE ROUTES

Instructions: ****OVERHANG MAY NOT EXCEED 25' FRONT AND/OR REAR; **ONLY ONE PIECE OF FREIGHT ALLOWED WHEN OVERWEIGHT IS INVOLVED; **BRIDGE AND ROUTE RESTRICTIONS 8-08 APPLY. SEE PERMIT CONDITIONS, WEIGHT RESTRICTED BRIDGE & ROUTE LIST, FOUR WEIGHT RESTRICTED MAPS

Travel: FROM 1/2/2014 THRU 1/2/2015

Authorized: ☐ Weekend ☐ Night ☐ Holiday ☐ Workday Commute Hour

Description of Load: HAULED/TOW
**MISCELLANEOUS CONSTRUCTION, MINING & FARM EQUIPMENT, UNLADEN, TRUSSES, BEAMS, JOISTS, CONCRETE PRODUCTS, REBAR, PIPE, UTILITY POLES, OFF-ROAD TIRES, STRUCTURAL & PLATE STEEL, MILITARY & DRILLING EQUIPMENT

Dimensions: **Width:** 12' 0" **Height:** 15' 0" **Length:** 110' 0"

Gross Weight: 120,638 **Total Axles:** 7 **Overhang:** **Front:** Legal **Rear:** Legal

Axle Spacing	1	13' 1"	2	4' 5"	3	4' 4"	4	33' 3"	5	4' 6"	6	4' 6"	7
Wheels	4		4		4		4		4		4		4
Wgt	18,000 (Steer weight)		51,188						51,450				

Figure 7.17. NDOT over-dimensional multi-trip permit form for Case Study IV.

Table 7.5. Multi-Trip OW Vehicle Input Information for Case Study IV.

Climatic Information		**OW Vehicle Axle Configuration**	
Parameter	***Input***	***Parameter***	***Input***
Climatic Station	Reno	*GVW, lb*	120,638
Related Miles Traveled	2,500	*Number of Axles*	7
		OW Vehicle Width, feet	12.0

Figure 7.18 presents the PDAC results attributable to the evaluated multi-trip OW vehicle at different percentile levels. The permanent deformation-based PDAC values were somehow higher than the fatigue cracking-based values. This is particularly observed at the 90th percentile estimate values. At the 50th percentile level and using 2,500 miles travelled, PDAC values of 559.45 and 526.71 US dollars were estimated for permanent deformation and fatigue cracking, respectively.

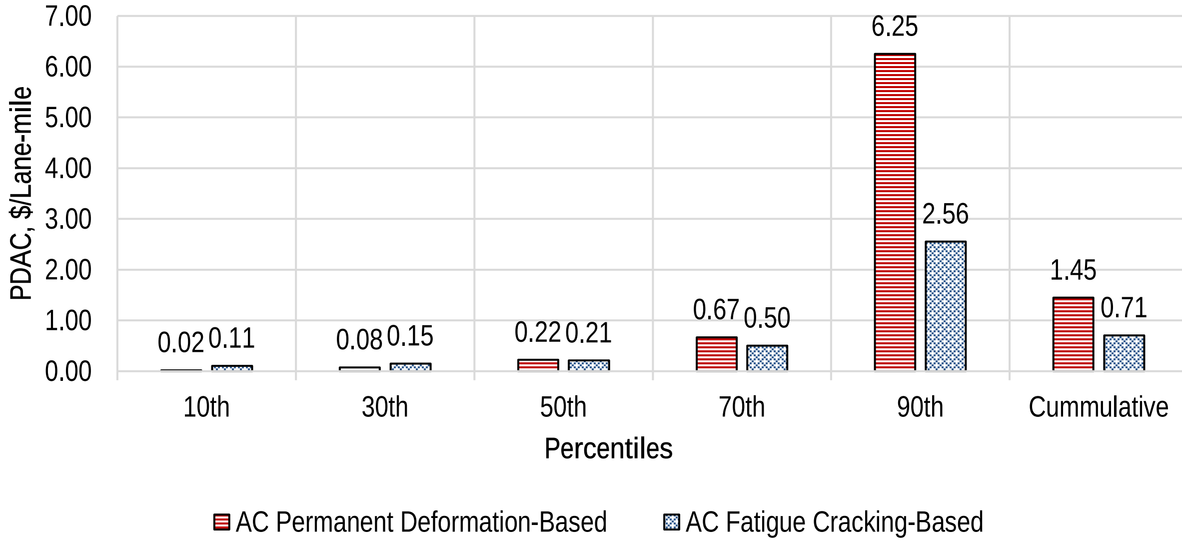
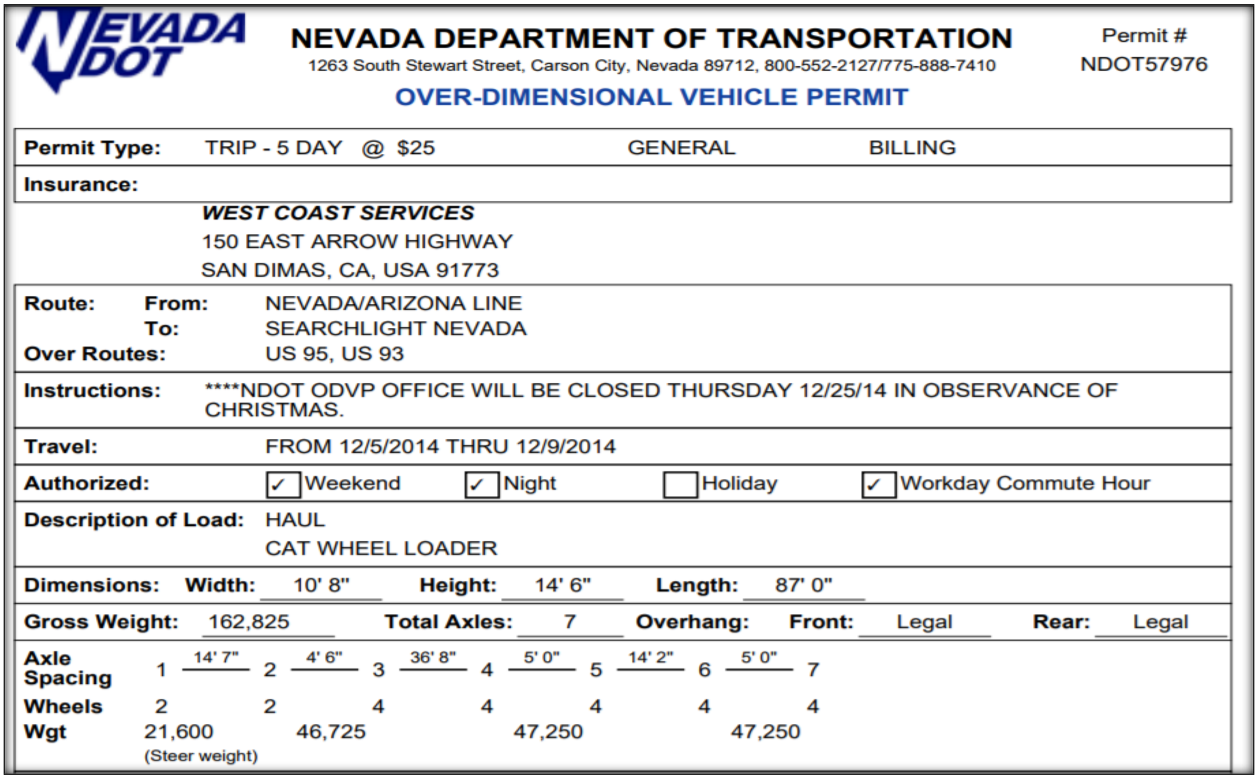


Figure 7.18. Multi-trip OW vehicle PDAC values in US dollars per lane mile for Case Study IV.

7.5 Comparative Analysis Between PDAC and OW Permit Fees from Surrounding States

In this section a comparative analysis is conducted between the PDAC attributable to an example OW vehicle calculated using OVAP and the estimated permit fee imposed by surrounding states for the same OW vehicle. Information on the OW vehicle evaluated in this comparison analysis was obtained from a NDOT single-trip permit form and is presented in Figure 7.19. The OW vehicle included one steering axle (single axle) and three tandem axle groups. The total GVW of the vehicle was 162,825 lb. The OW vehicle traveled in southern Nevada over US route 95 and US route 93 with a total VMT of 47 miles as presented in Figure 7.20. The width of the vehicle is 10 feet 8 inch. Table 7.6 presents a summary of the input information.

Figure 7.21 presents PDAC output results in US dollars per lane-mile attributable to the OW vehicle used in the comparative analysis. Because the OW movement was completed in December, pavement temperatures were significantly low. Therefore, permanent deformation-based PDAC values were zero. Fatigue cracking-based PDAC values ranged between 0.52 and 1.37 US dollars per lane mile. Figure 7.22 presents PDAC values for the entire trip (47 miles) with values ranging between 25.35 and 63.62 US dollars per trip based on pavement temperature during the OW movement.



NEVADA DOT

NEVADA DEPARTMENT OF TRANSPORTATION
1263 South Stewart Street, Carson City, Nevada 89712, 800-552-2127/775-888-7410
OVER-DIMENSIONAL VEHICLE PERMIT

Permit #
NDOT57976

Permit Type:	TRIP - 5 DAY @ $25		GENERAL		BILLING		
Insurance:							
	WEST COAST SERVICES 150 EAST ARROW HIGHWAY SAN DIMAS, CA, USA 91773						
Route: From:	NEVADA/ARIZONA LINE						
To:	SEARCHLIGHT NEVADA						
Over Routes:	US 95, US 93						
Instructions:	****NDOT ODVP OFFICE WILL BE CLOSED THURSDAY 12/25/14 IN OBSERVANCE OF CHRISTMAS.						
Travel:	FROM 12/5/2014 THRU 12/9/2014						
Authorized:	☑ Weekend	☑ Night	☐ Holiday	☑ Workday Commute Hour			
Description of Load:	HAUL CAT WHEEL LOADER						
Dimensions:	**Width:** 10' 8"	**Height:** 14' 6"	**Length:** 87' 0"				
Gross Weight: 162,825	**Total Axles:** 7	**Overhang:**	**Front:** Legal	**Rear:** Legal			

Axle	1	2	3	4	5	6	7
Spacing	14' 7"	4' 6"	36' 8"	5' 0"	14' 2"	5' 0"	
Wheels	2	2	4	4	4	4	4
Wgt	21,600 (Steer weight)	46,725		47,250		47,250	

Figure 7.19. NDOT over-dimensional permit form for comparative analysis between Nevada and other surrounding states.

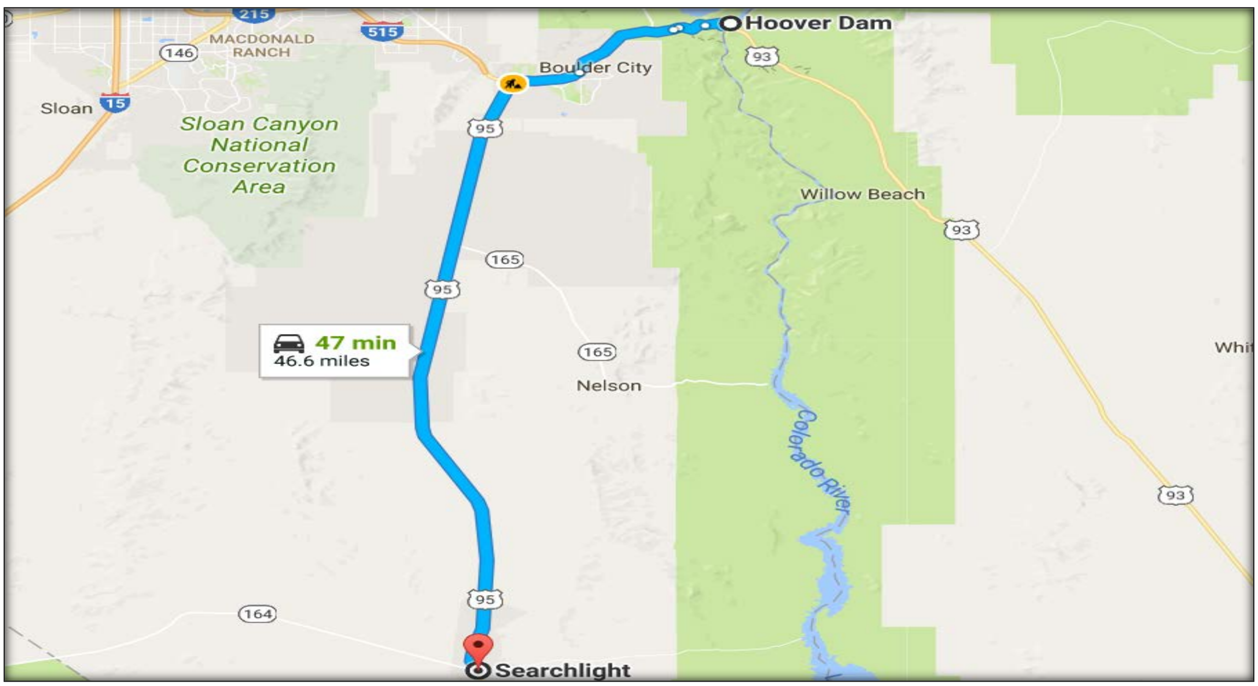


Figure 7.20. Route of OW vehicle evaluated in the comparative analysis between Nevada and other surrounding states.

Table 7.6. Summary Input Information of OW Vehicle Used in Comparative Analysis between Nevada and other Surrounding States.

<table>
<tr><th colspan="5">Climatic Information</th><th colspan="3">General Analysis Information</th></tr>
<tr><th colspan="2">Parameter</th><th colspan="3">Input</th><th colspan="2">Parameter</th><th>Input</th></tr>
<tr><td colspan="2">NDOT District</td><td colspan="3">I</td><td colspan="2">Operational Speed</td><td>55 mph</td></tr>
<tr><td colspan="2">Climatic Station</td><td colspan="3">Las Vegas</td><td colspan="2">VMT</td><td>47</td></tr>
<tr><td colspan="2" rowspan="2">Month of Move</td><td colspan="3" rowspan="2">December</td><td colspan="2">Pavement Structure</td><td>8 inch/8 CAB</td></tr>
<tr><td colspan="2">AADTT</td><td>2,500</td></tr>
<tr><th colspan="5">OW Vehicle Axle Configuration</th><th colspan="3" rowspan="4">Axle Grouping Table</th></tr>
<tr><td colspan="2">GVW, lb</td><td colspan="3">162,825</td></tr>
<tr><td colspan="2">Number of Axles</td><td colspan="3">7</td></tr>
<tr><td colspan="2">OW Vehicle Width, ft</td><td colspan="3">10.7</td></tr>
<tr><th>Axle No.</th><th>Designation</th><th>feet</th><th>inch</th><th>No. of Tires</th><th>Axle Group</th><th>Axle Group Load, lb</th><th>Widebase (Y/N)</th></tr>
<tr><td>1</td><td>L_{1-2}</td><td>14</td><td>7</td><td>2</td><td>1</td><td>21,600</td><td>N</td></tr>
<tr><td>2</td><td>L_{2-3}</td><td>4</td><td>6</td><td>4</td><td>2-3</td><td>46,725</td><td>N</td></tr>
<tr><td>3</td><td>L_{3-4}</td><td>36</td><td>8</td><td>4</td><td>4-5</td><td>47,250</td><td>N</td></tr>
<tr><td>4</td><td>L_{4-5}</td><td>5</td><td>0</td><td>4</td><td>6-7</td><td>47,250</td><td>N</td></tr>
<tr><td>5</td><td>L_{5-6}</td><td>14</td><td>2</td><td>4</td><td colspan="3" rowspan="3"></td></tr>
<tr><td>6</td><td>L_{6-7}</td><td>5</td><td>0</td><td>4</td></tr>
<tr><td>7</td><td></td><td></td><td></td><td>4</td></tr>
</table>

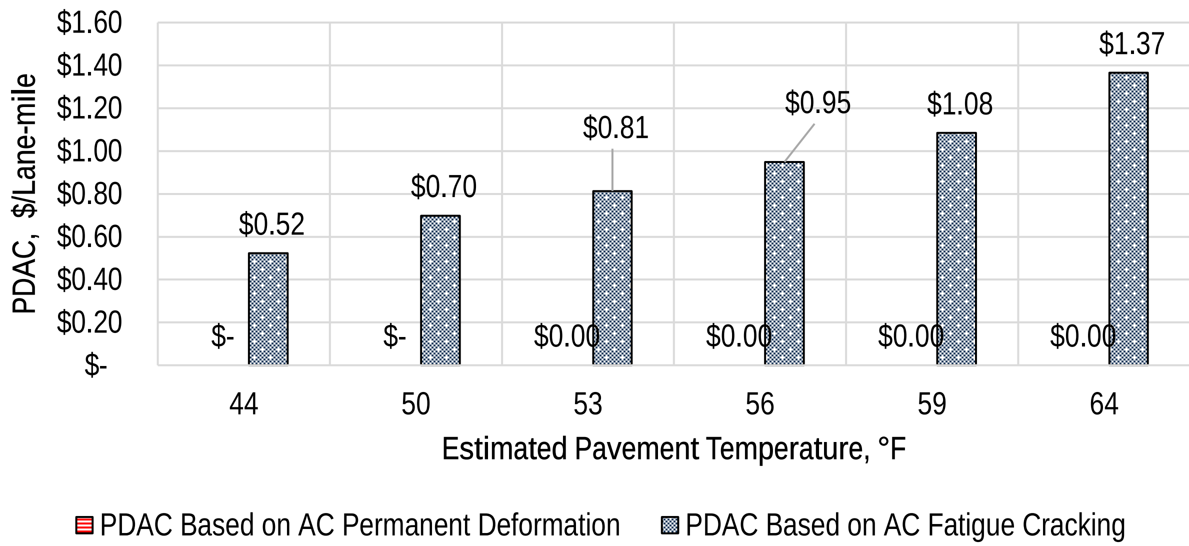


Figure 7.21. PDAC values in US dollars per lane mile for comparative analysis between Nevada and other surrounding states.

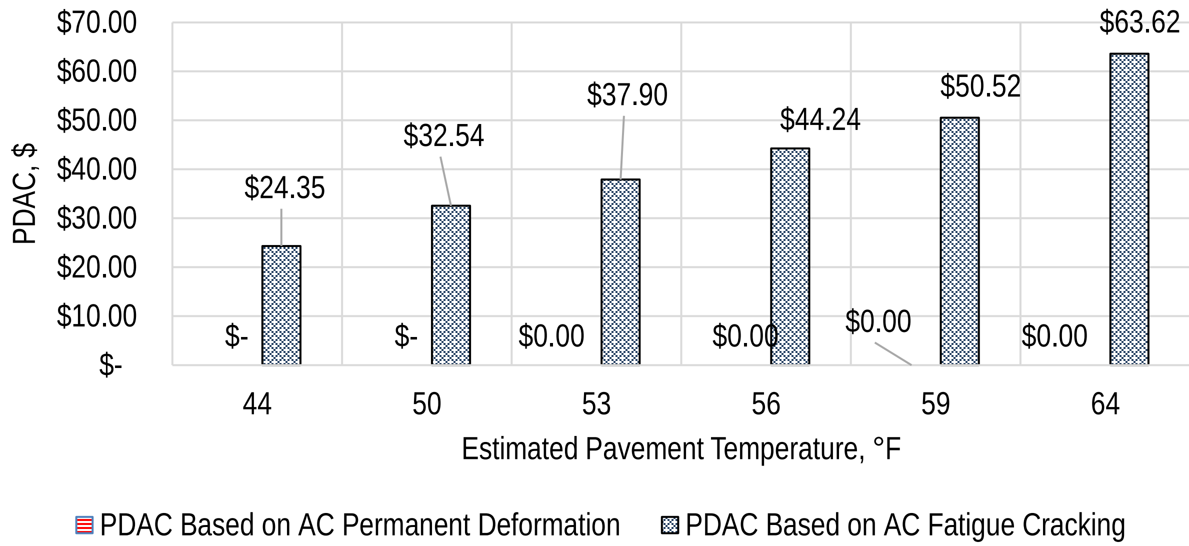


Figure 7.22. PDAC values in US dollars per trip for comparative analysis between Nevada and other surrounding states.

The single-trip permit fees imposed by six different SHAs to allow the operation of the evaluated OW vehicle within their jurisdictions were determined using information provided by Papagiannakis.[9] The SHAs considered in this analysis included: Arizona, California, Idaho, Oregon, Utah, and Washington. The same trip distance of 47 miles was considered in this comparative analysis.

Figure 7.23 presents a color-coded US map showing Nevada and the other six states considered along with their corresponding OW permit fee structure type (i.e., flat fee, weight-distance, distance, flat fee plus infrastructure damage fee). Table 7.7 summarizes the different permit fees calculated for the analysis OW vehicle. For Nevada, two fees are presented: the current flat fee of 25 US dollars for single OW trip, and the determined PDAC range of 24.3 to 63.6 US dollars (see Figure 7.22). Arizona implements a permit fee structure mainly based on distance. In fact, this state charges 12 US dollars to OW vehicles traveling less than 50 miles plus a use fuel fee of 16 US dollars which produces a total permit fee of 28 US dollars. California specifies a flat fee and charges 16 US dollars plus a fee depending on any infrastructure damage caused by the OW vehicle movement. Idaho specifies a flat fee of 71 US dollars regardless of GVW and trip distance. Utah uses a special weight-distance fee structure that includes a flat fee of 60 US dollars plus increments mainly depending on GVW and trip distance. A total permit fee of 140 US dollars was estimated for the evaluated OW vehicle move in Utah. Washington and Oregon specify a weight-distance fee structure resulting in 226.7 and 76.6 US dollars, respectively.

Evidently, SHAs uses OW vehicle permit fee structures that are not uniform producing different permit fees for the same OW vehicle. As presented in Section 2.1, most SHAs uses permit fee structures based on ranges of GVW and trip duration. However, efforts to quantify pavement damage and PDAC from OW vehicle moves are significant and would become more practical as SHAs implement ME-based analysis and design methodologies

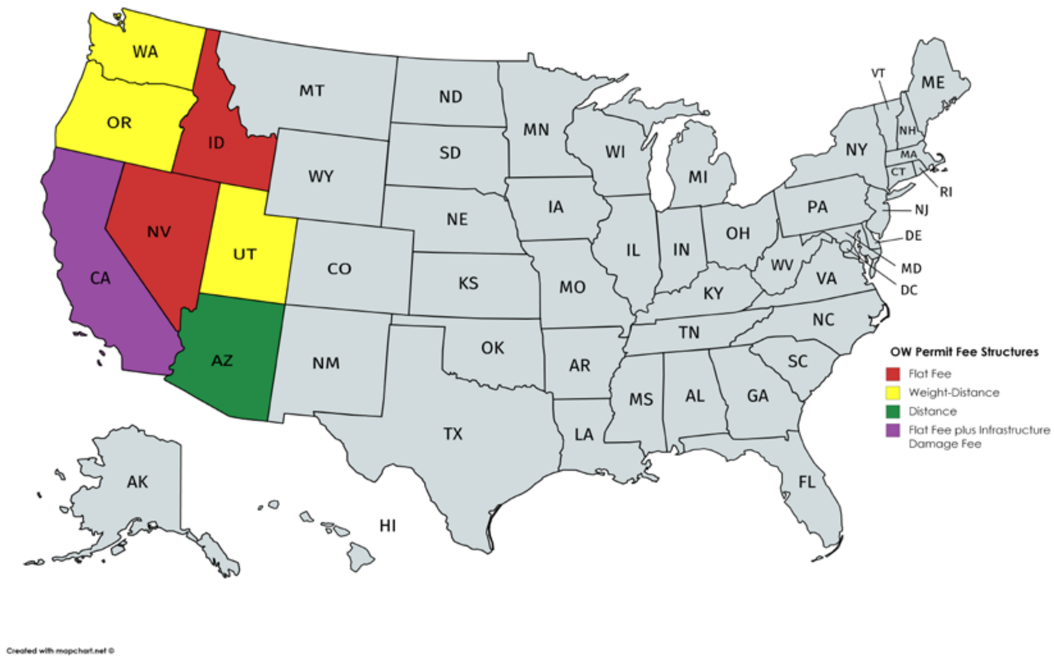


Figure 7.23. United States map showing single-trip permit fees for different SHAs.

Table 7.7. Single Trip Permit Fees.

Agency	Permit Fee Structure	Fee, Dollars
Arizona	Distance	28
California	Flat fee plus infrastructure repair fee	16+
Idaho	Flat Fee	71
Nevada	Flat Fee (Current)	25
	PDAC	24.4- 63.6
Oregon	Weight-Distance	76.6
Utah	Weight-Distance	140
Washington	Weight Distance	226.7

7.6 Comparison Analysis Between Current Nevada Fees and PDAC

A comparative analysis between the estimated annual fees collected by NDOT in 2013 using flat fee structure and those estimated using PDAC was conducted. The analysis considered single-trip OW vehicles, excluding OS only vehicles. As presented in Section 3.1, NDOT issued a total of 29,775 permits in 2013 (see Figure 3.2) out of which 10,974 permits were for OS/OW and OW only vehicles. The permits were categorized based on GVW as shown in Table 7.8. The average GVW for each range was also determined from the data. The most frequent GVW range was (110,001 – 130,000) with 3,979 entries. In contrast, only three permits were issued in 2013 to OW vehicles with GVW higher than 500,000. Table 7.8 shows an estimate of the total fees collected within each category in 2013 while considering a flat fee of 25 US dollars. It is estimated that nearly 274,500 US dollars were collected from the considered OW permits during that year.

Table 7.8. Estimation of Total Fees Collected in 2013 using Flat Fee and PDAC Fee Structures.

GVW Ranges	*Average OW Vehicle GVW*	*Number of Permits*	*Current Flat Fee, US Dollars*	*PDAC, US Dollars/lane-mile*				*RSL, %*	*Total PDAC, US Dollars*		
				Las Vegas Station	*Reno Station*	*Elko Station*	*Average*		*VMT: 25*	*VMT: 50*	*VMT:100*
80,001 - 90,000	85,385	126	3,150	0.43	0.64	0.55	0.54	80	1,361	2,722	5,443
90,001 - 100,000	95,400	87	2,175	0.50	0.73	0.65	0.63		1,090	2,181	4,362
100,001 - 110,000	106,000	1422	35,550	0.49	0.72	0.62	0.61		17,348	34,697	69,394
110,001 - 130,000	119,225	3979	99,475	0.63	0.91	0.82	0.79		62,603	125,206	250,412
130,001 - 150,000	133,950	1662	41,550	0.83	1.16	0.96	0.98		32,686	65,372	130,744
150,001 - 200,000	171,500	1159	28,975	1.62	2.37	2.03	2.01		46,515	93,029	186,058
200,001 - 250,000	236,400	2336	58,400	4.23	6.42	5.86	5.50		257,116	514,231	1,028,463
250,001 - 500,000	271,200	200	5,000	4.83	7.34	6.92	6.36		25,453	50,907	101,813
> 500,000	612,500	3	75	22.81	33.51	33.83	30.05		1,803	3,606	7,212
Total		***10,974***	***274,350***	***Total Yearly Estimated PDAC, Dollars***					***445,975***	***891,950***	***1,783,901***

To compare the collected revenue using the current Nevada flat fee and estimated revenue using PDAC methodology, different assumptions were made. First, a representative OW vehicle configuration for each GVW category was selected from the database. For example, the configuration representing the 90,001 to 100,000 range comprises of steering, tandem and tridem axle groups. Second, each representative OW configuration was given the corresponding average GVW as listed in Table 7.8. Next, a pavement structure was selected from those included in the *Overweight Vehicle Analysis Package.* In this analysis, the structure comprising 8 inch AC over 8 inch CAB was selected for all cases. *Las Vegas*, *Reno*, and *Elko* climatic stations were selected and the corresponding mean annual pavement temperatures were determined to be 81, 64, and 54°F, respectively. These pavement temperatures were implemented in PDAC analyses. Remaining service life of 80% was assumed, suggesting that OW trips are conducted on pavement sections with good condition.

Table 7.8 lists the PDAC in US dollars per lane mile corresponding to each GVW category. Average PDAC values are also listed. For example, average PDAC for (80,000 – 90,000) category is 0.54 US dollars. It is observed that average PDAC values increase with increasing GVW. In fact, the PDAC value for the highest GVW range is over 30 US dollars per lane mile. This is a significantly high value corresponding to an OW vehicle hauling over 600,000 lb. Three VMT levels (25, 50, and 100 miles) were assumed for PDAC computation. When using 25 VMT to each single trip in the analysis, the total estimated revenue per year was 445,975 US dollars, which represents 63% increase in revenue when compared to fees levied by NDOT during 2013. On the other hand, if a 50 VMT is assumed, the total estimated fees collected increases to nearly 900,000 US dollars. Finally, when assuming 100 VMT, the total estimated fees increases to nearly 1,800,000 US dollars.

The PDAC methodology presented in this report provided significant increases in revenue from OW permit fee collection. The greatest increment in fees are derived from the heaviest GVW categories more particularly from the 200,001 to 250,000 GVW category. This is more clearly observed in Figure 7.24 where the number of permits issued in 2013, the collected flat fees, and those fees estimated using PDAC are presented. In 2013, the flat fees resulted in an estimated 55,975 US dollars from OW vehicles within the 200,001 – 250,000 GVW category. It is observed that when applying PDAC, the estimated OW fees for this GVW category increased significantly. For example, for 25 VMT the estimated fees derived from this category increased to 257,116 US dollars, nearly five times the estimated amount collected in 2013. It is also observed that the estimated PDAC for the lightest OW categories is comparable to that collected using flat fee structure. This suggests that while OW vehicles with low GVW (80,000 – 110,000) are somehow paying their fair share under the current Nevada flat fee structure, OW vehicles with high GVW can be underpaying their share of the pavement damage attributable to their operation in Nevada.

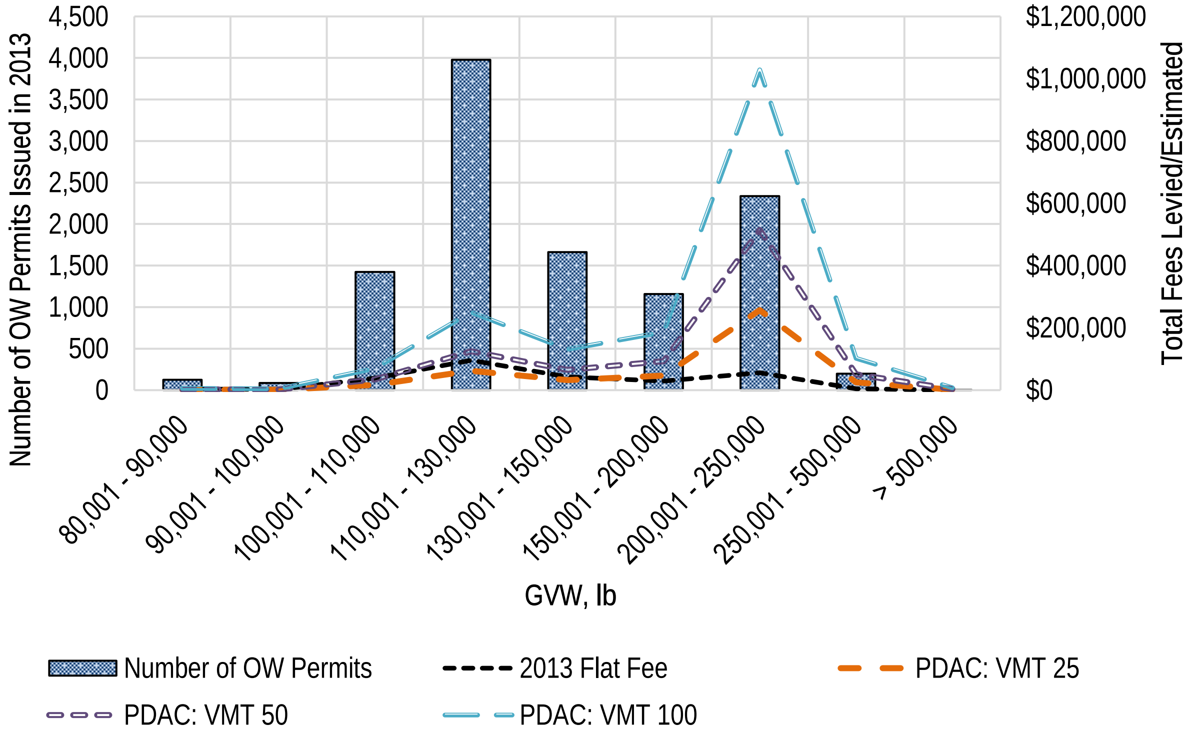


Figure 7.24. Summary of estimated fees by GVW categories.

7.7 Assessment of Pavement Damage from Bus Rapid Transit in Nevada

BRT buses operate on high frequency routes and can contribute to the overall pavement deterioration in Nevada. In fact, some bus models exceed axle limits even without any passengers on board. Consequently, BRT buses are allowed to operate under exemption policies. For instance, the Regional Transportation Commission (RTC) of Southern Nevada has a waiver for the operation of BRT on state owned local streets.(18) Similarly, the Northern Nevada RTC introduced in 2009 a BRT express service that also exceeded the State imposed limits.(114) When running at high ridership, some BRT buses' single axle load can be well above 20,000 lb. While the benefits provided by BRT and other public transit systems are not in discussion, SHAs should be aware and should be able to evaluate the pavement damage exerted by these vehicles.

As part of this research effort, rutting- and fatigue-based LEF for three different BRT buses operating in Northern and Southern Nevada were determined. Pavement responses corresponding to all cases of bus loading and climatic conditions were obtained using the 3-D Move Analysis software. The critical pavement responses were then used in locally calibrated performance models (see Section 2.3.1) to estimate LEFs for the various BRT vehicles. In the assessment of pavement damage, simplified and extended methodologies were developed. The interaction between pavement temperature and axle loading for both Northern and Southern Nevada BRT buses was considered in the extended method, which considered seasonal distributions of pavement temperature and bus passenger ridership to determine LEFs. In the simplified method, pavement responses from a single combination of analysis temperature with either the average ridership loading or Gross Axle Weight rating (GAWR) were considered.

7.7.1. Data Requirements

Figure 7.25 shows the evaluated BRT and schematics of their axle configurations. The Double Decker and the Irisbus currently operate in Las Vegas. The New Flyer bus operates in Reno and in Las Vegas. The Double Decker bus is a tri-axle high capacity double deck bus designed to carry up to 120 people. The Irisbus is a three-axle articulated vehicle with a maximum capacity of 120 passengers. The New Flyer bus is also an articulated transit vehicle with a maximum capacity of over 110 passengers. Load and axle specifications for the buses in question were obtained from NDOT and from manufacturer's specifications and are presented in Table 7.9. Average bus loads and GAWR loads, which represent the maximum allowable weight that can be placed on an individual axle are presented. Tire inflation pressure and the distance between axles are also shown in Table 7.9.

The same pavement structure (8 inch AC over 10 inch CAB over SG) was used for both Northern and Sothern Nevada locations along with representative layer properties already presented in Table 3.6. The surface layers consisted of a typical AC layer with a PG64-28NV and a PG76-22NV polymer-modified asphalt binder for Northern (i.e., Reno) and Southern (i.e., Las Vegas) Nevada, respectively. Representative dynamic modulus values corresponding to the asphalt mixtures used in Northern and Southern Nevada were used in 3D-Move Analysis for the calculation of pavement responses. The BRT bus operational speed for both locations was assumed to be 15 mph.

Double Decker **Irisbus** **New Flyer**

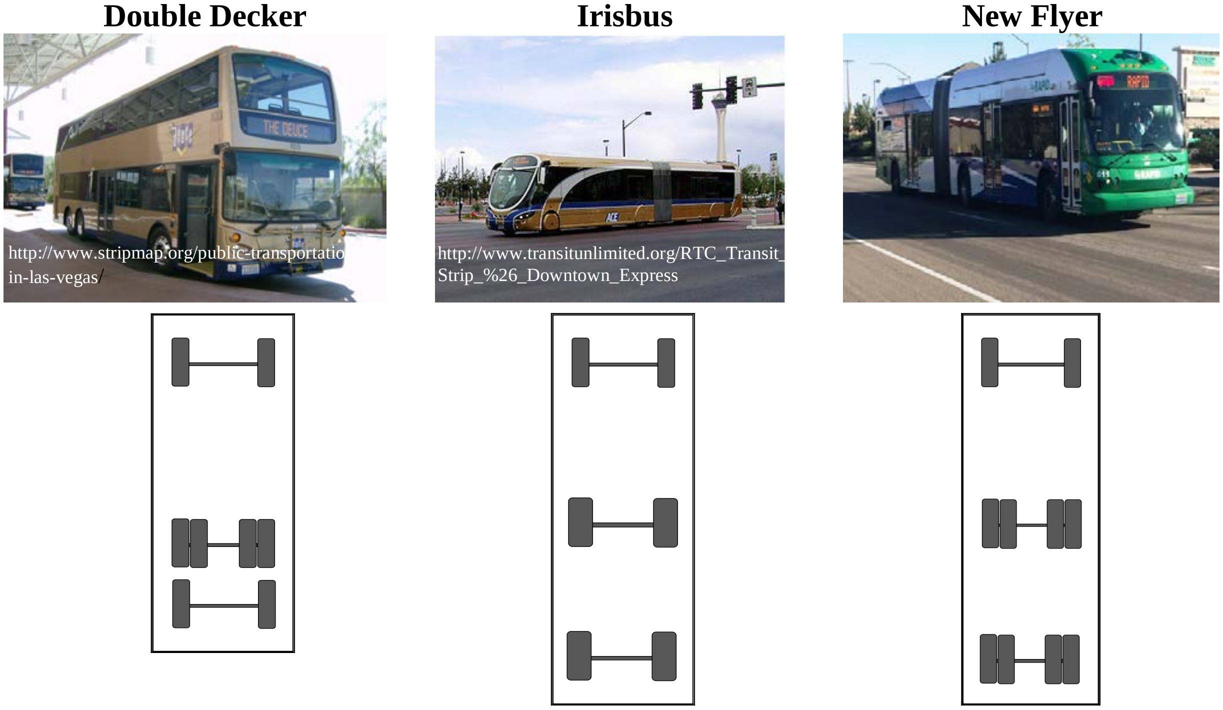


Figure 7.25. Evaluated BRT buses.

Table 7.9. Axle and Loading Configurations of BRT Buses.

Axle and Loading Configurations										
Bus		Double Decker			Irisbus Civis			New Flyer		
Axle		Front[a]	Drive	Rear	Front[a]	Drive[b]	Rear[b]	Front[a]	Drive	Rear
Axle Type		Single	Dual	Single	Single	Single	Single	Single	Dual	Dual
Tire Inflation, psi		120	85	110	130	130	130	120	120	120
Mean Axle Load, lb	**Las Vegas**	14,412	19,041	13,417	13,845	24,655	22,000	13,340	20,592	25,515
	Reno							11,750	15,010	24,990
GAWR, lb		15,653	20,944	14,330	16,094	28,660	25,574	14,780	24,250	27,760
Axle Spacing, inch		Front-Drive	Drive-Rear		Front-Drive	Drive-Rear		Front-Drive	Drive-Rear	
		294	58		211	266		224	293	
Bus Max Capacity		120			120			110		

Air temperature and other climatic data corresponding to the Las Vegas McCarran and Reno Tahoe LTPP weather stations were assembled for the study. Seasonal pavement temperature distributions were then estimated using the FVCM temperature model developed by Alavi et al.[56] The effective pavement temperatures (Teffs) for asphalt rutting and fatigue cracking were also calculated for each location using the same climatic information. The Teff is a single constant temperature at which an amount of a given distress (i.e., asphalt rutting or fatigue) would be equivalent to that which would occur from the seasonal temperature fluctuation throughout the annual temperature cycle.[18] The pavement damage analysis was conducted using the pavement temperature distribution as well as the calculated Teffs.

Equation 15 and Equation 16 were used in the calculation of rutting and fatigue cracking effective temperatures Teffs.[18] Here, z equals the critical depth in inch. $Freq$ is the loading frequency in Herz. MAAT is the mean annual air temperature for the evaluated location in degrees Fahrenheit. $\sigma MMAT$ corresponds to the standard deviation of the mean air temperature. Rain and sunshine correspond to the annual cumulative rainfall depth in inch and the mean annual wind speed in miles per hour, respectively. The calculated AC permanent deformation Teff values of 110°F and 97°F were found for Las Vegas and Reno, respectively. Likewise, the calculated fatigue Teff for Las Vegas and Reno were 97°F and 69°F, respectively.

$$T_{eff\_Rut} = 14.62 - 3.361 Ln(Freq) - 10.940\,(z) + 1.121\,(MAAT) + 1.718\,(\sigma MAAT) - 0.431(Wind) + 0.333(Sunshine) + 0.08\,(Rain) \quad [15]$$

$$T_{eff\_Fat} = -13.95 - 2.332(Freq)^{0.5} + 1.006\,(MAAT) + 0.876(\sigma MAAT) - 1.186(Wind) + 0.549(Sunshine) + 0.071\,(Rain) \quad [16]$$

Because axle loading on buses directly depends on the number of passengers being transported, ridership reports were used to calculate the total axle loads. An entire year, hour by hour ridership report was obtained for the BRT buses operating in Las Vegas. On the other hand, hourly average or typical hourly passenger ridership was available for the BRT bus in Northern Nevada. To estimate axle loads, a weight of 150 lb per passenger was used, and then the total load was distributed over the bus axles proportionally to the GAWR load carried by each axle.

7.7.2. Analysis Methodology

As mentioned before, the 3D-Move Analysis software was used to calculate the pavement responses under the various BRT axles. The calculated responses were then used in the calibrated performance models to determine the number of load repetitions to failure for the various distresses. The maximum vertical compressive strain, ε_r, and the maximum tensile strain, ε_t, at the middle and bottom of AC layer were used, respectively. The determination of ε_r and ε_t allowed for the determination of LEFs using the locally calibrated performance models. Two types of analyses, an extended and a simplified analysis were implemented in this study. In the case of the extended analysis, pavement responses from multiple pavement analyses based on seasonal distributions of hourly pavement temperatures at different levels of axle loading representing the variability in ridership were considered for each BRT bus. In the simplified analysis, instead of using pavement temperature and ridership history, pavement responses from a single combination of Teff analysis temperature in conjunction with either the AVG or the GAWR axle loadings were used.

The influence of the variation in both, pavement temperature and BRT axles' loadings based on the ridership data in the calculation of LEFs was capture in the extended analysis. Multiple pavement analyses were needed to obtain the required pavement responses, one for each combination of ridership loading and temperature. Normal distributions and the cumulative difference delineation (CDD) method was implemented to determine representative ranges for pavement temperature and ridership values.[18] For instance, the experimental plan shown in Table 7.10 was generated for the Double Decker bus. In this case, a total of 240 pavement analyses were undertaken for the determination of the seasonal LEFs of the various Double Decker bus axles. Similar experimental plans were developed for the other evaluated BRT buses and an overall total of 2,880 pavement analyses were completed for the extended analysis. LEFs for each of the BRT axles were determined using the mathematical expression shown in Equation 4. The combined BRT bus LEF is obtained by adding the LEFs of all the axles in a bus.

Table 7.10. Double Decker BRT Bus Experimental Plan.

<table>
<tr><td rowspan="8">Extended Analysis</td><td rowspan="3">Axle</td><td colspan="2">Period:</td><td colspan="3">Period 1: Morning</td><td colspan="3">Period 2: Afternoon</td><td colspan="3">Period 3: Evening</td><td colspan="3">Period 4: Night</td></tr>
<tr><td rowspan="2">Season</td><td rowspan="2">Pav. Temp</td><td colspan="12">Axle Loads due to Ridership</td></tr>
<tr><td>25th</td><td>50th</td><td>75th</td><td>25th</td><td>50th</td><td>75th</td><td>25th</td><td>50th</td><td>75th</td><td>25th</td><td>50th</td><td>75th</td></tr>
<tr><td>Front</td><td rowspan="5">Winter
Spring
Summer
Fall</td><td>10th</td><td colspan="3" rowspan="5">15 Different Combinations</td><td colspan="3" rowspan="5">15 Different Combinations</td><td colspan="3" rowspan="5">15 Different Combinations</td><td colspan="3" rowspan="5">15 Different Combinations</td></tr>
<tr><td rowspan="2">Drive</td><td>30th</td></tr>
<tr><td>50th</td></tr>
<tr><td rowspan="2">Rear</td><td>70th</td></tr>
<tr><td>90th</td></tr>
<tr><td rowspan="4">Simplified Analysis</td><td>Axle</td><td colspan="2" rowspan="4">Rutting, and Fatigue Effective Temperatures</td><td colspan="6">Average Ridership Loading</td><td colspan="6">GAWR</td></tr>
<tr><td>Front</td><td colspan="6" rowspan="3">1 Combination</td><td colspan="6" rowspan="3">1 Combination</td></tr>
<tr><td>Drive</td></tr>
<tr><td>Rear</td></tr>
</table>

7.7.3. Analysis Results

The individual axle LEFS and the combined LEF for each of the BRT buses were calculated using the extended and simplified analysis methods described above based on rutting and fatigue cracking distresses. Figure 7.26 and Figure 7.27 summarize the calculated LEFs based on AC permanent deformation and AC fatigue cracking, respectively. All four BRT buses analyzed in this study along with the individual LEFs for the steering, drive, and rear axles are presented. LEFs based on the extended analysis are presented for each of the four seasons. On the other hand, the calculated LEFs based on the simplified method are shown for the GAWR and AVG axle loadings.

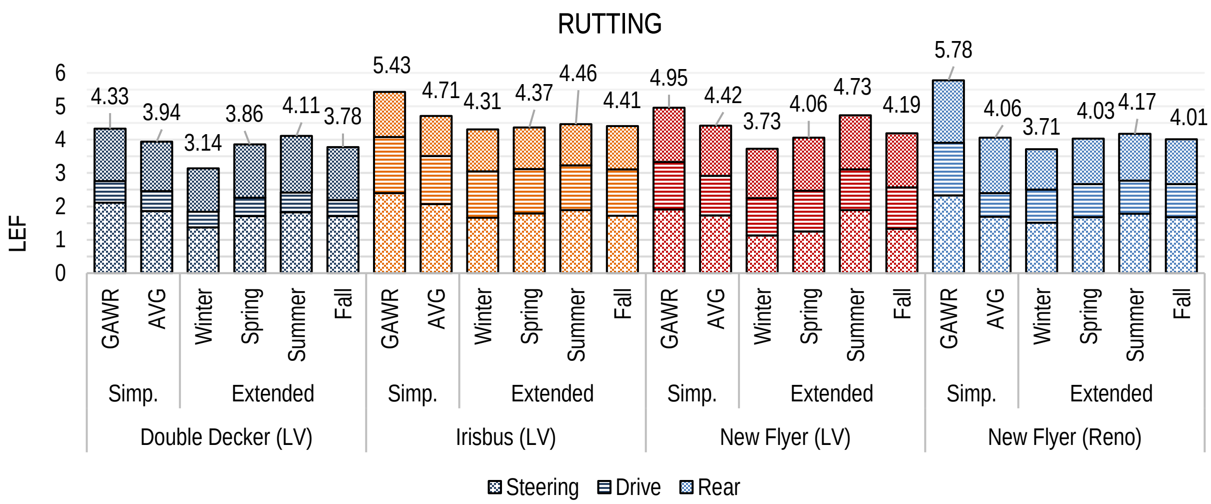


Figure 7.26. LEFs results based on AC permanent deformation.

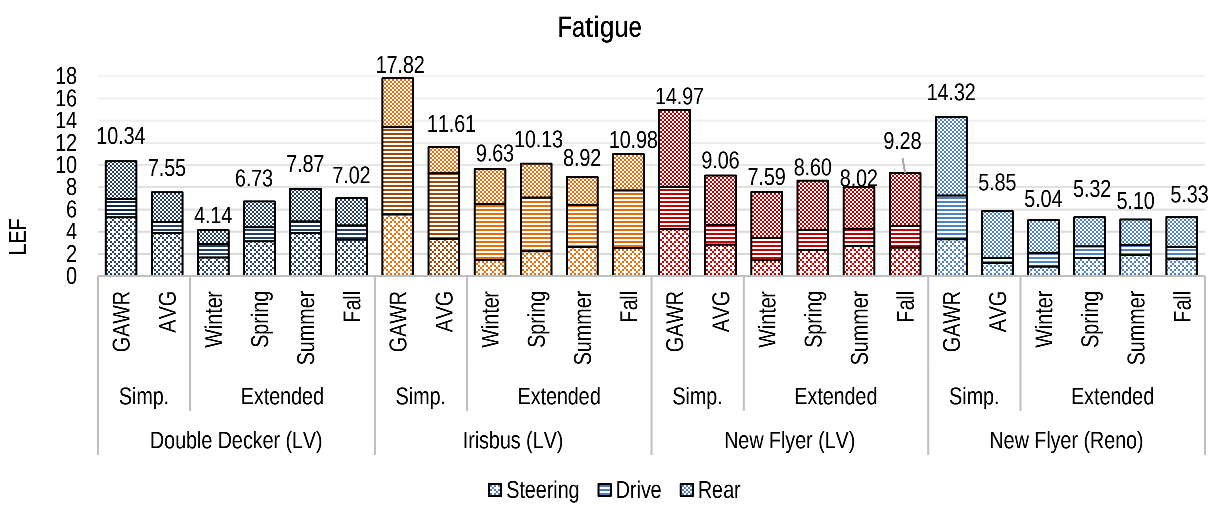


Figure 7.27. LEFs results based on AC fatigue cracking.

In general, the results showed that fatigue LEFs were consistently higher than those calculated for rutting. It is clear that in most cases the fatigue LEFs are more than twice the rutting LEFs. The difference between both LEFs is even greater when the simplified GAWR LEFs was considered. Consequently, for a given pavement structure, fatigue damage is anticipated to be predominant under the passage of a specific BRT bus. When accounting for seasonal variations in the extended analysis, summer rutting LEFs were generally higher than those determined for the winter months. In contrast, the rutting LEFs determined for fall and spring showed similar values. This is mainly due to similar ridership and climatic conditions presented in both seasons. When considering the fatigue criteria, with only the exception of the Double Decker steering and rear axles, higher LEFs were obtained during the spring and fall seasons, when intermediate temperatures are experienced.

For the BRT buses operating in Las Vegas, the Double Decker and the Irisbus exhibited the lowest and highest LEFs, respectively. When comparing the Irisbus to the New Flyer in Las Vegas, the latter one exhibited lower rutting and fatigue based LEFs. As presented before, the Irisbus has widebase tires on the drive and rear axles while the New Flyer bus has single axles dual tire configuration. When considering the New Flyer (Reno) LEFs, they are generally lower than those determined for the Irisbus and New Flyer in Las Vegas. This is mainly due to the lower axle ridership loading and the different climatic conditions experienced in Reno.

The daily frequencies of the BRT buses in conjunction with the calculated LEFs were employed to determine the number of ESALs that BRT buses would produce in a 10-year period. Figure 7.28 presents the number of ESALs using extended and simplified analysis based on both rutting and fatigue LEFs. From the simplified method, the GAWR and the AVG equivalencies were used in the calculation of ESALs. On the other hand, the AVG seasonal LEFs were calculated from the seasonal LEFs determined using the extended methodology and were then employed in the calculation of ESALs. Because fatigue LEFs are generally higher than the rutting ones, they produced a higher number of ESALs after the 10-year period. It is also clear that rutting LEFs from extended and simplified methods produced a similar number of ESALs for a specific bus. Figure 7.28 also indicates that all BRT buses in Las Vegas would result in number of ESALs ranging from 1.01 to 1.36 million when rutting LEFs were used. When rutting LEFs are used in Reno, the number of ESALs would be around half of those in Las Vegas. If instead, fatigue LEFs were used in Reno, the estimated ESALs would double.

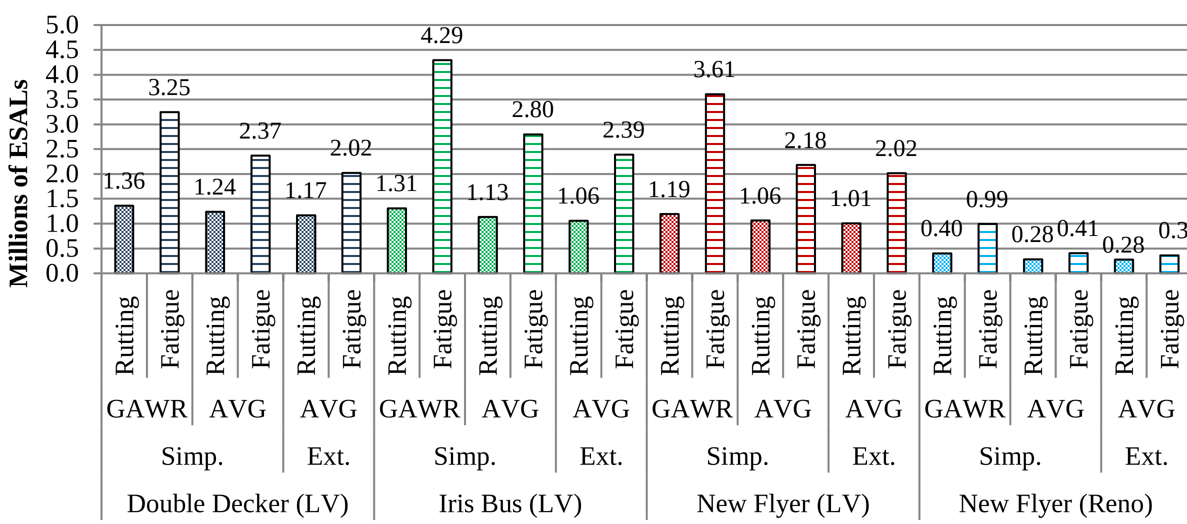


Figure 7.28. Estimated ESALs after 10 years for various BRT buses.

Results showed that pavement damage from BRT buses in Nevada was significantly influenced by the variability in climatic conditions and passenger ridership. From the two distress types evaluated in this case study, fatigue-based LEFs were significantly higher that the rutting-based LEFs. The extra pavement damage exerted by the BRT buses should not be ignored by SHAs as it may lead to a rapid pavement deterioration.

7.8 Summary

This chapter presented information relative to the determination of PDAC for different analysis scenarios. First, PDAC values were estimated for four different OW vehicles in Nevada. All the analyses were conducted using the Excel package OVAP developed as part of this research effort. Additionally, two comparative analyses were presented. The first analysis compared the PDAC attributable to a selected OW vehicle calculated using OVAP to the estimated permit fee for the same OW vehicle imposed by surrounding states. The PDAC values calculated using the methodology presented in this report were comparable to the fees imposed by surrounding states. The second analysis compared the estimated annual fees collected by NDOT in 2013 using flat fee structure to those estimated using OVAP. It was found that the estimated fees derived from the implementation of PDAC methodology to impose fair and just fees could result in a significant increase in revenue from OW permit fees' collection. The assessment of pavement damage form BRT buses is Nevada was also presented in this chapter. The LEF values for three type of BRT buses were determined.

CHAPTER 8 SUMMARY, CONCLUSSIONS, AND RECOMMNEDATIONS FOR FUTURE WORK

Highway agencies issue permits to commercial vehicles exceeding established federal weight limits. These permits are usually associated with a nominal fee often ignoring the pavement damage caused by OW vehicle move. Recently, several studies have evaluated the true impact of these vehicles on flexible pavements. These studies suggested cost allocation schemes correlating pavement damage and associated cost using different type of input parameters. In this report, a ME based approach was proposed for the analysis of cost allocation attributable to pavement damage under an OW vehicle move. The approach considers several input parameters and provides a realistic methodology to assess pavement damage from single-trip and multi-trip OW scenarios. Because of the ME nature of the presented approach, the use of locally calibrated performance models was implemented.

Although the same cost allocation methodology was used to determine PDAC for both single-trip and multi-trip scenarios, the necessary steps to conduct the analysis were different. The single trip analysis was based on a deterministic assessment that yields a single output solution. On the other hand, the pavement damage from multi-trip permitted vehicles was addressed with a probabilistic analysis using MC simulations, which yields output distributions of pavement damage and PDAC. The probabilistic analysis considered variations in any potentially influential critical factors during the duration of a multi-trip permit. Such factors included axle load and configuration, pavement structure, material properties, and environmental conditions encountered during a permit period.

As part of this study a ten-year NDOT over-dimensional permit database containing 367,595 entries was analyzed. Along with the ten-year permit database, thousands of actual over-dimensional permit forms which described GVW and the entire axle and load configurations of the permitted vehicles were analyzed. The purpose of the analysis was the identification and classification of trends, GVW, axle loads/tire loads and other important characteristics of the OW vehicle movements in Nevada. This analysis enabled the design of a comprehensive experimental plan of pavement analysis required to model OW vehicles under the different loading, pavement temperature, and speed conditions found in Nevada.

A comprehensive pavement responses database was populated by conducting over 8,000 3D-Move pavement analyses while considering representative pavement structures and other variety of numerous factors presented in the experimental plan. The vertical compressive strain at mid-depth (ε_r) of AC layers and maximum horizontal tensile strain at bottom of AC layers (ε_t) were particularly evaluated as they are directly correlated to AC permanent deformation and AC fatigue cracking, respectively.

The comprehensive database of critical pavement responses was used in the development of the user-friendly Excel package, *Overweight vehicle Analysis Package* – OVAP. OVAP conducts pavement damage and PDAC analyses of single-trip and multi-trip OW vehicles without the need for conducting individual and time-prohibited pavement analyses for the different axle groups in the OW analysis vehicle.

To illustrate the PDAC methodology, four case examples were evaluated. The analyses were carried out using OVAP. Input information was obtained from NDOT Over-dimensional permits. A comparative analysis between the PDAC of a single OW vehicle as obtained from the *Overweight Vehicle Analysis Package* and the permit fee levied by different SHAs to allow its operation was also presented. It was found that several factors can influence the calculation of PDAC. Therefore engineers and transportation officials should be prudent and exercise good judgment when quantifying the necessary input values for the cost allocation analysis. Another analysis was conducted comparing the revenue collected using the current Nevada fee structure and estimated revenue using PDAC. It was found that the estimated revenue derived from the implementation of PDAC methodology could produce significant increments in revenue from OW permit fee collection even when assuming strictly-conservative input values. It was also found that OW vehicles with high GVW can be severely underpaying the pavement damage associated to their operation in Nevada

The presented methodology provides useful ways to assess pavement damage from OW vehicles, eliminating the need for conducting individual deterministic pavement analysis assessments. Though the NDOT OW database did not include illegal OW data, the methodology would still work for illegal OW traffic analysis. It would be desirable to secure illegal OW traffic data, so the influence and associated pavement damage costs on the highway network could be estimated. Considering the results and information presented in this study, the following observations were made.

- PDAC values were influenced by environmental conditions and pavement structure. NDOT should be aware of the circumstances in which the pavement damage potential is the greatest (i.e., high temperature for rutting and combination of intermediate temperature and axle loads for fatigue, low structural capacity) and accordingly, regulate the issuance of OW permits. This regulation may consider limiting or restricting permit issuance under high damage potential conditions.
- Observed fatigue-based PDAC values were greater than rutting-based PDAC values. This suggests that for Nevada conditions OW vehicles have the potential to induce greater AC fatigue cracking damage than AC permanent deformation damage.
- The presented PDAC methodology was useful as it provides an estimation of pavement damage induced by different OW vehicles having different axle loads and configurations. This methodology can be used as the basis for permit fee cost allocation structure for both single- and multi-trip OW vehicle scenarios in Nevada. However, it is suggested to evaluate different permit fee options before their implementation.
- Both the deterministic and probabilistic pavement damage methodologies mimic the operation of OW and a reference (standard) vehicles, enabling comparison and determination of relative pavement damage factors. NDOT could use the presented methodology to obtain information for regulating OW vehicle operations in terms of OW vehicle axle configurations. It could also be used to limit OW vehicle types operating on specific highway facility.
- Trucking companies could use the method to optimize vehicle axle configurations and axle loading distributions in order to minimize pavement damage, and consequently increase their revenue by reducing permit fees.

- It is suggested that NDOT could start requesting an estimate of the number of miles associated to each permitted vehicle during the permit application process. This should be done until a solid distribution can be assembled and included it in the probabilistic analysis.

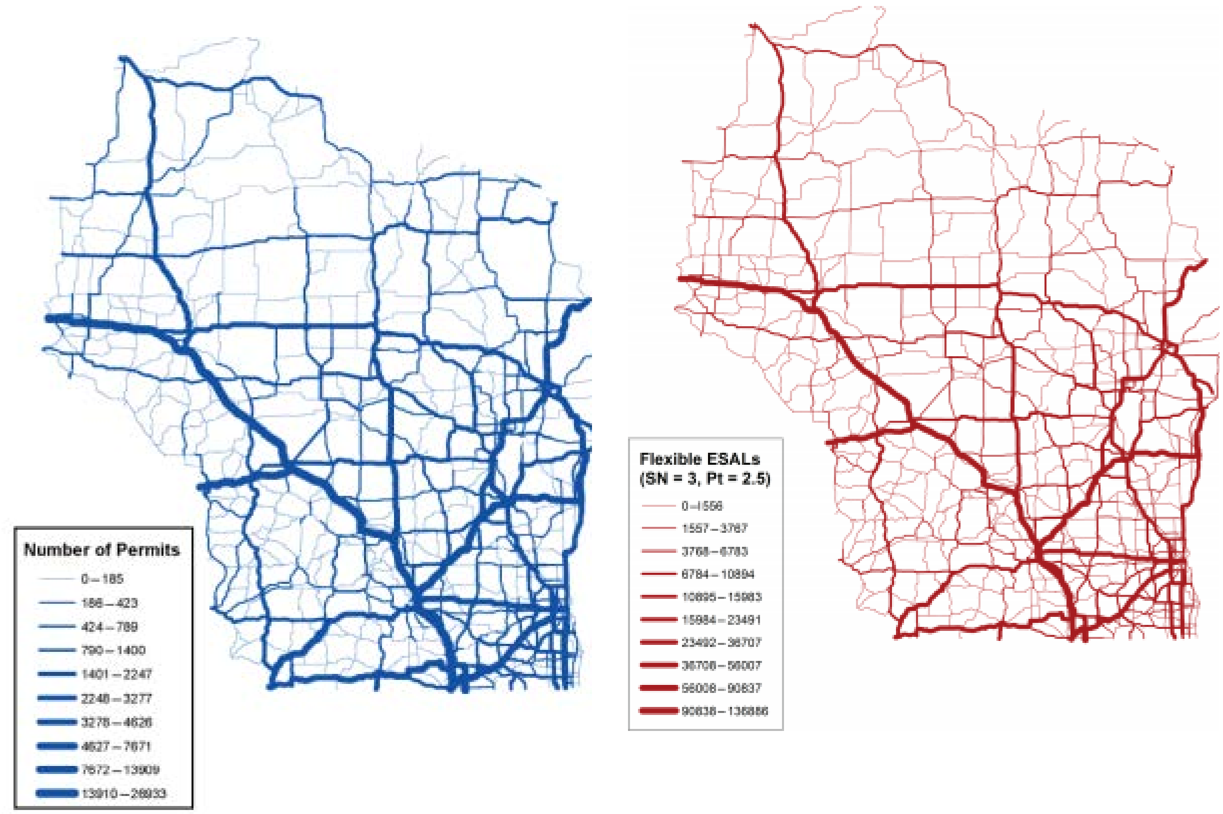
8.1 Future Research Work

Geographical Information Systems (GIS) are widely used by SHAs as they provide a framework for visual representation and integration of multiple databases (e.g. traffic volumes, PMS, route restrictions). GIS tools increase the efficiency in analysis and operations activities. Physical mapping and integration in GIS provide a proper background structure for OW permit fee systems. The development of a GIS-based automated tool to aid in the integration of data needed for implementation of the PDAC methodology is recommended. This integration can improve operations and decision-making practices during the OW permit fee application process. This can also enhance and facilitate the evaluation of pavement damage in Nevada by enabling the visualization of different traffic spatial patters and relationships.

As part of this study, a methodology based on ME analysis was developed for the estimation of permit fees for single and multi OW trips in Nevada. During the permit application process a route or set of routes are assigned to each OW permitted vehicle. A GIS-based tool could enhance the permit application process by facilitating routing identification, and assignment of input values. For instance, once the GIS-automated tool identifies routing in the permit, it can assign material properties, traffic inputs, and pavement condition inputs to the different pavement segments. Bridge, seasonal, and structural route restrictions could also be integrated within a GIS platform. Consequently, different transportation, traffic and pavement analysis could be conducted. For instance, the GIS framework can be used to estimate the percentage of overweight trucks on certain road segments. Furthermore, estimating the frequency of permitted vehicles over different routes. This information can be implemented for overweight enforcement purposes and could provide insights for pavement management systems scenarios.

GIS applications using OW permit data are already being implemented by different SHAs in the nation. For instance, in 2014 Dayan et al. presented a methodology to map OS/OW permits to a Linear Reference System using GIS.(63) In this study the authors developed multiple applications using the mapped permit data. The applications enable The West Virginia Department of Motor Vehicles to properly quantify illegal OW vehicles and to analyze routes that needed more frequent rehabilitation.

In a different project Titi et al. integrated a database with more than 95,000 OW single-trip vehicle permits in Wisconsin. Applications to map the cumulative number of permits, vehicle weight, flexible pavement ESALs across the Wisconsin highway network were generated.(16) The maps allow Wisconsin DOT officials to visualize the most heavily traveled segments in Wisconsin which could help in the design of adequate rehabilitation programs. The authors also generated origin-destination maps showing the cities and locations with unusual high levels of permit vehicle traffic. For instance, Figure 8.1 presents some of the maps generated in the referenced study. Figure 8.1(a) shows the aggregated number of permits on each road segment in Wisconsin. Figure 8.1(b) presents the cumulative number of ESALs during the analysis process.



(a) (b)

Figure 8.1. Maps showing aggregated OW permits in Wisconsin: (a) Cumulative number of single-trip permits, and (b) cumulative number of flexible ESALs. (*Figures obtained from Titi et al. study).*

Furthermore, it is recommended that NDOT continues with the implementation of the PDAC methodology into a GIS information system framework that could integrate the traffic, pavement management systems (PMS), and routing databases to the PDAC methodology. This integration could significantly increase the efficiency and revenue from OS/OW permit operations. As the technology to accomplish this objective is already available and currently being implemented by several agencies, the probability of success is high.

CHAPTER 9 REFERENCES

1. Ostria SJ (2003) Evaluation of US Commercial Motor Carrier Industry Challenges and Opportunities.
2. Bilal MK, Irfan M, Ahmed A, Labi S, & Sinha KC (2010) A Synthesis of Overweight Truck Permitting.
3. FHWA (February 5, 2017) Oversize/Overweight Load Permits. (FHWA, Office of Freight Management and Operations).
4. Nevada Department of Transportation (2017) General Permit Information, https://www.nevadadot.com/doing-business/commercial-vehicles/commercial-vehicle-permits/general-permit-information, Asceed 8/31/2017.
5. Banerjee A & Prozzi JA (2015) Practical Approach for Determining Permit Fees for Overweight Trucks. *Transportation Research Record: Journal of the Transportation Research Board* (2478):93-102.
6. Dey, K., Chowdhury, M., Pang, W., Putman, B., and Chen, L. (2014). "Estimation of pavement and bridge damage costs caused by overweight trucks." *Transportation Research Record: Journal of the Transportation Research Board*(2411), 62-71.
7. Dey, K. C., Chowdhury, M., Wiecek, M. M., and Dunning, A. (2015). "Infrastructure damage-cost-recovery fee for overweight trucks: Tradeoff analysis framework." *Journal of Transportation Engineering*, 141(7), 04015008.
8. Dong, Q., Huang, B., Shu, X., Zhou, C., and Maxwell, J. (2014). "Use of Finite Element Analysis and Fatigue Failure Model to Estimate Costs of Pavement Damage Caused by Heavy Vehicles." *Transportation Research Record: Journal of the Transportation Research Board*(2455), 54-62.
9. Papagiannakis, A. T. (2015). *Practices for Permitting Superheavy Load Movements on Highway Pavements* (No. Project 20-05, Topic 45-14).
10. 378, N. C.H.R.P.S. State Highway Cost Allocation Studies. Transportation Research Board, Washington, 2008.
11. Administration, F. H. Transporation Policies Studies. https://www.fhwa.dot.gov/policy/otps/costallocation.cfm. Accessed May 20, 2014.
12. Mingo R, D., Pavement Damage Analysis Tool (*PaveDat*) Documentation, Developed under DTFH61-11-Q-00048, 3-30-2012 Draft.
13. Talking Freight Presentation Transcript; Pavement Damage Analysis Tool (*PaveDat*) for Overweight truck Permit Calculation, June 2012, Federal highway Administration. https://ops.fhwa.dot.gov/freight/fpd/talking_freight/index.htm (accessed 6/15/2015)
14. NCHRP (2004). "*Guide for mechanistic-empirical design of new and rehabilitated pavement structures*." *National Cooperative Highway Research Program* Transportation Research Board of the National Academies, Washington, DC.
15. Sebaaly P, Siddharthan R, & Huft D (2003) Impact of heavy vehicles on low-volume roads. *Transportation Research Record: Journal of the Transportation Research Board* (1819):228-235.
16. Titi H, Coley N, Latifi V, & Matar M (2014) Characterization of Overweight Permitted Truck Routes and Loads in Wisconsin. *Transportation Research Record: Journal of the Transportation Research Board* (2411):72-81.

17. Wang H, Zhao J, & Wang Z (2015) Impact of Overweight Traffic on Pavement Life Using Weigh-In-Motion Data and Mechanistic-Empirical Pavement Analysis. *9th International Conference on Managing Pavement Assets*.
18. Hajj EY, Batioja-Alvarez D, & Siddharthan R (2016) Assessment of Pavement Damage from Bus Rapid Transit: Case Study for Nevada. *Transportation Research Record: Journal of the Transportation Research Board* (2591):70-79.
19. Banerjee A & Prozzi JA (2015) Practical Approach for Determining Permit Fees for Overweight Trucks. *Transportation Research Record: Journal of the Transportation Research Board* (2478):93-102.
20. Wu, D., Zhao, J., Liu, H., & Yuan, C. (2017). The assessment of damage to Texas highways due to oversize and overweight loads considering climatic factors. *International Journal of Pavement Engineering*, 1-13.
21. Dey, K. C., Putman, B. J., Chowdhury, M., & Bhavsar, P. (2015). Quantification of Accelerated Pavement Serviceability Reduction Due to Overweight Truck Traffic. In *Transportation Research Board 94th Annual Meeting* (No. 15-5378).
22. Owusu-Ababio, S., & Schmitt, R. (2015). Analysis of Data on Heavier Truck Weights: Case Study of Logging Trucks. *Transportation Research Record: Journal of the Transportation Research Board*, (2478), 82-92.
23. Wang, H., Al-Qadi, I., & Huft, D. (2014). Pavement-Dependent Load Limits: Case Study in South Dakota for Different Tire Configurations. Transportation Research Record: Journal of the Transportation Research Board, (2456), 107
24. Banerjee, Ambarish, Jorge Prozzi, and Prasad Buddhavarapu. "Framework for determining load equivalencies with DARWin-ME." *Transportation Research Record: Journal of the Transportation Research Board* 2368 (2013): 24-35.
25. Chowdhury, M., Putman, B., Pang, W., Dunning, A., Dey, K., Chen, L., 2013. Rate of Deterioration of Bridges and Pavements as Affected by Trucks Tech. Rep. FHWA-SC-13-05. Prepared by Clemson University for the South Caroline Department of Transportation, Clemson, SC
26. Dong, Q., & Huang, B. (2013). FIELD MEASUREMENT OF PAVEMENT RESPONSES UNDER SUPER HEAVY LOAD.
27. Banerjee, A., Prozzi, J., & Prozzi, J. (2012). Evaluating the effect of natural gas developments on highways: Texas case study. *Transportation Research Record: Journal of the Transportation Research Board*, (2282), 49-56.
28. Ohio Department of Transportation, (2009), Impact of Permitted Trucking on Ohio's Transportation System and Economy.
29. Al-Qadi, I. L., & Wang, H. (2009). *Pavement damage due to different tire and loading configurations on secondary roads* (No. NEXTRANS Project No. 008IY01). NEXTRANS
30. Sadeghi, J. M., & Fathali, M. (2007). Deterioration analysis of flexible pavements under overweight vehicles. *Journal of Transportation Engineering*, *133*(11), 625-633.
31. TJAN, A., & FUNG, C. (2005). Determination of equivalent axle load factor of trailer with multiple axles on flexible pavement structures. *Journal of the Eastern Asia Society for Transportation Studies*, *6*, 1194-1206.
32. Boilé, M., Narayanan, P., & Ozbay, K. (2003). Impact of buses on highway infrastructure: Case study for New Jersey State. *Transportation Research Record: Journal of the Transportation Research Board*, (1841), 32-40.

33. Suleiman, N., & Varma, A. (2002). Methodology to assess impacts of alternative truck configurations on flexible highway pavement systems. *Transportation Research Record: Journal of the Transportation Research Board*, (1809), 148-159.
34. Gibby, R., Dawson, R., & Sebaaly, P. (1996). Local urban transit bus impact on pavements. *Journal of transportation engineering*, *122*(3), 215-217.
35. Dey, K., Chowdhury, M., Pang, W., Putman, B., and Chen, L. (2014). "Estimation of pavement and bridge damage costs caused by overweight trucks." *Transportation Research Record: Journal of the Transportation Research Board*(2411), 62-71.
36. Dey, K. C., Chowdhury, M., Wiecek, M. M., and Dunning, A. (2015). "Infrastructure damage-cost-recovery fee for overweight trucks: Tradeoff analysis framework." *Journal of Transportation Engineering*, 141(7), 04015008.
37. Bilal, M., Irfan, M., Ahmed, A., Labi, S., & Sinha, K. (2010). A synthesis of overweight truck permitting. Publication FHWA/IN/JTRP-2010/12. West Lafayette, Indiana: Joint Transportation Research Program, Indiana Department of Transportation and Purdue University.
38. Chen, Xingwei, et al. "Evaluation of superheavy load movement on flexible pavements." *International Journal of Pavement Engineering* 14.5 (2013): 440-448.
39. Dong, Q., Huang, B., Shu, X., Zhou, C., and Maxwell, J. (2014). "Use of Finite Element Analysis and Fatigue Failure Model to Estimate Costs of Pavement Damage Caused by Heavy Vehicles." *Transportation Research Record: Journal of the Transportation Research Board*(2455), 54-62.
40. Weissmann, A. J., Weissmann, J., Papagiannakis, A., & Kunisetty, J. L. (2012). Potential Impacts of Longer and Heavier Vehicles on Texas Pavements. *Journal of Transportation Engineering*, *139*(1), 75-80.
41. Prozzi, J., Murphy, M., Loftus-Otway, L., Banerjee, A., Kim, M., Wu, H., Prozzi, J.P., Hutchison, R., Harrison, R., Walton, C.M., Weissmann, J., Weissmann, A. (2012). "*Oversize/Overweight Vehicle Permit Fee Study*," *Rep. No. FHWA/TX-13/0-6736-2*, U.S. DOT, Federal Highway Administration.
42. Hajek, Jerry, Susan Tighe, and Bruce Hutchinson. (1998) "Allocation of pavement damage due to trucks using a marginal cost method." *Transportation Research Record: Journal of the Transportation Research Board* 1613 50-56.
43. Moffett, D., and Whitford, R., (1995) Development of annual permit procedure for overweight trucks on Indiana highways, Joint Highway Research Project, Purdue University.
44. Bai, Y., Schrock, S. D., Mulinazzi, T.E., Hou, W., Liu, C., and Firman, U. (2010). "Estimating Highway Pavement Damage Costs Attributed to Truck Traffic," *Final Rep., Mid-America Transportation Center*, Lincoln, NE.
45. Tirado, C., Carrasco, C., Mares, J. M., Gharaibeh, N., Nazarian, S., and Bendana, J. (2010). "Process to Estimate Permit Costs for Movement of Heavy Trucks on Flexible Pavements," *Transportation Research Record*, *2154*, Washington, D.C., 187-196.
46. Hong, F., Prozzi, J. A., and Prozzi, J. (2007). "A New Approach for Allocating Highway Costs," *J. Transportation Research Forum*, 46(2), 5-19.
47. Timm, D.H., Turochy, R.E., and Peters, K. D. (2007). "Correlation between Truck Weight, Highway Infrastructure Damage and Cost," *Final Rep., DTFH61-05-Q-00317*, Auburn University Research Center
48. Straus, S.H., and J. Semmens. Estimating the Cost of Overweight Vehicle Travel on Arizona Highways. Arizona Department of Transportation, Phoenix, 2006

49. Boile, M., Ozbay, K., and Narayanan P. (2001). "*Infrastructure Costs Attributable to Commercial Vehicles*," *Rep. No. FHWA-NJ-2001-030*, U.S. DOT, Federal Highway Administration.
50. Roberts, F.L. and L. Djakfar, "Cost of Pavement Damage Due to Heavier Loads on Louisiana Highway," Transportation Research Record, No. 173, TRB, National Research Council, Washington, D.C., (2000) pp. 3-11.
51. Hajek, Jerry, Susan Tighe, and Bruce Hutchinson. "Allocation of pavement damage due to trucks using a marginal cost method." *Transportation Research Record: Journal of the Transportation Research Board* 1613 (1998): 50-56.
52. Hajj, E., Sebaaly, P., and Nabhan, P. (2015). "Manual for Designing Flexible Pavements in Nevada Using AASHTOWare Pavement-ME Design." Nevada Department of Transportation.
53. Oh, J., Fernando, E., and Lytton, R. (2007). "Evaluation of damage potential for pavements due to overweight truck traffic." *Journal of transportation engineering*, 133(5), 308-317.
54. 3D-Move Analysis software® V2.1. (2013). Reno, NV. Available online at: http://www.arc.unr.edu/Software.html#3DMove, last accessed October 20, 2017.
55. AASHTO Guide for Design of Pavement Structures. (1993) AASHTO, Washington, D.C.
56. Alavi, M., Pouranian, M., and Hajj, E. (2014). "Prediction of asphalt pavement temperature profile with finite control volume method." *Transportation Research Record: Journal of the Transportation Research Board*(2456), 96-106.
57. Siddharthan, R. V., J. Yao, and P. E. Sebaaly. Pavement Strain from Moving Dynamic 3D Load Distribution. (1998) Journal of Transportation Engineering, Vol. 124, No. 6 , pp. 557–566.
58. Siddharthan, R.V., N. Krishnamenon, M. El-Mously, and P.E. Sebaaly. Validation of a Pavement Response Model Using Full-Scale Field Tests.(2002) Journal of Pavement Engineering, Vol. 3, No. 2, pp. 85–93.
59. Coleri E & Harvey JT (2011) Evaluation of laboratory, construction, and performance variability by bootstrapping and monte carlo methods for rutting performance prediction of heavy vehicle simulator test sections. *Journal of Transportation Engineering* 137(12):897-906.
60. Hand A & Epps A (2000) Effects of test variability on mixture volumetrics and mix design verification. *ASPHALT PAVING TECHNOLOGY* 69:635-674.
61. Kazemi SF & Shafahi Y (2013) An Integrated Model Of Parallel Processing And PSO Algorithm For Solving Optimum Highway Alignment Problem. *ECMS*, pp 551-557.
62. Balducci P, Stowers J, Mingo R, Cohen H, & Wolff H (2009) Nevada Highway Cost Allocation Study. (Compilation Report, Batelle, Pacific Northwest Division, Richland, Washington).
63. Dayan, S., Nichols, A., Chou, C., Yoo, S., Nguyen, T., Pennington, E. (2014) Methodology to Map Rutes from truck Permit Database , Using a Linear Reference System and Network Analysis. *Transportation Research Record: Journal of the Transportation Research Board* (2460).

APPENDIX A AC Mid-Depth Temperature Profiles in Nevada

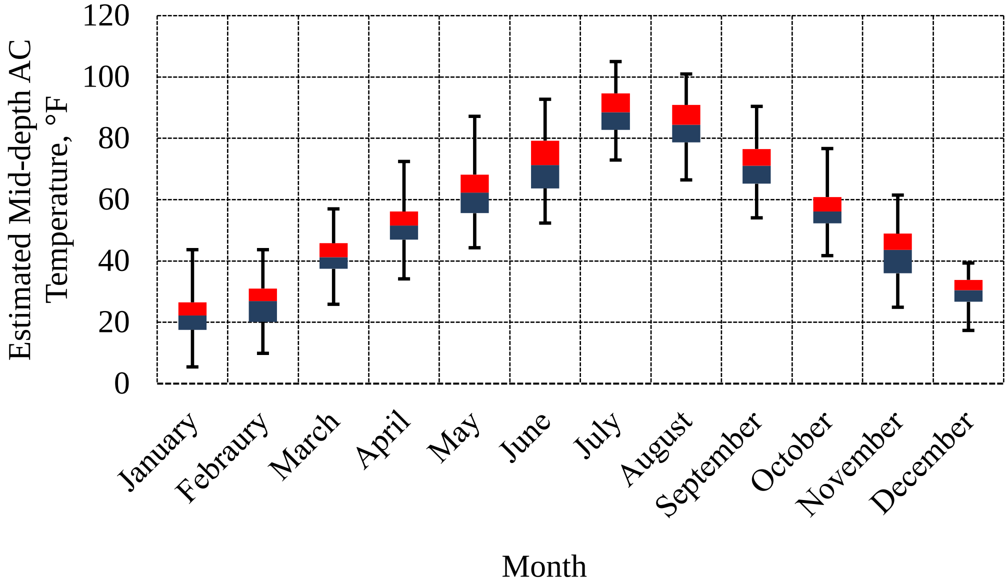


Figure A. 1: Estimated Mid-depth AC temperature for Elko station.

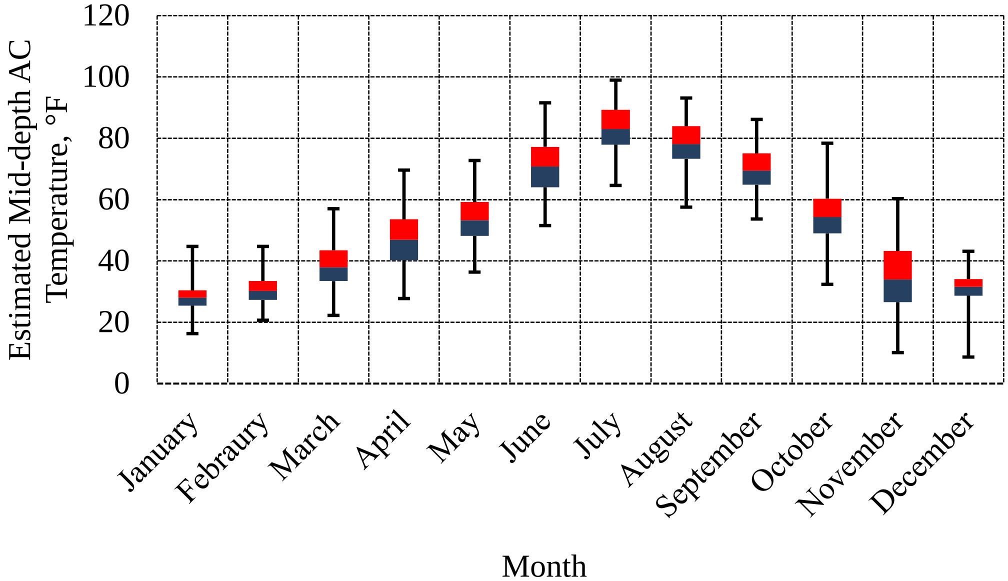


Figure A. 2: Estimated Mid-depth AC temperature for Ely station.

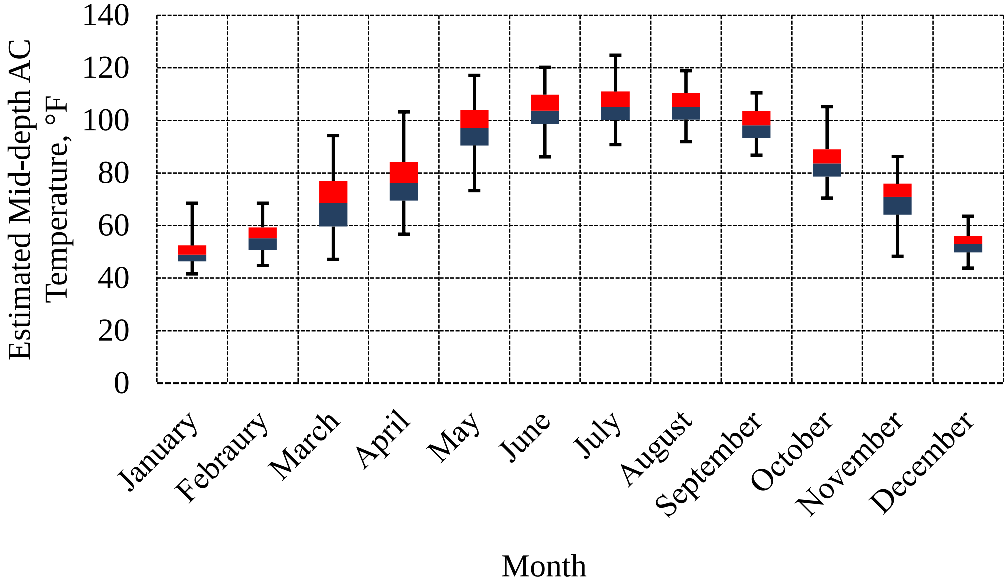


Figure A. 3: Estimated Mid-depth AC temperature for Las Vegas station.

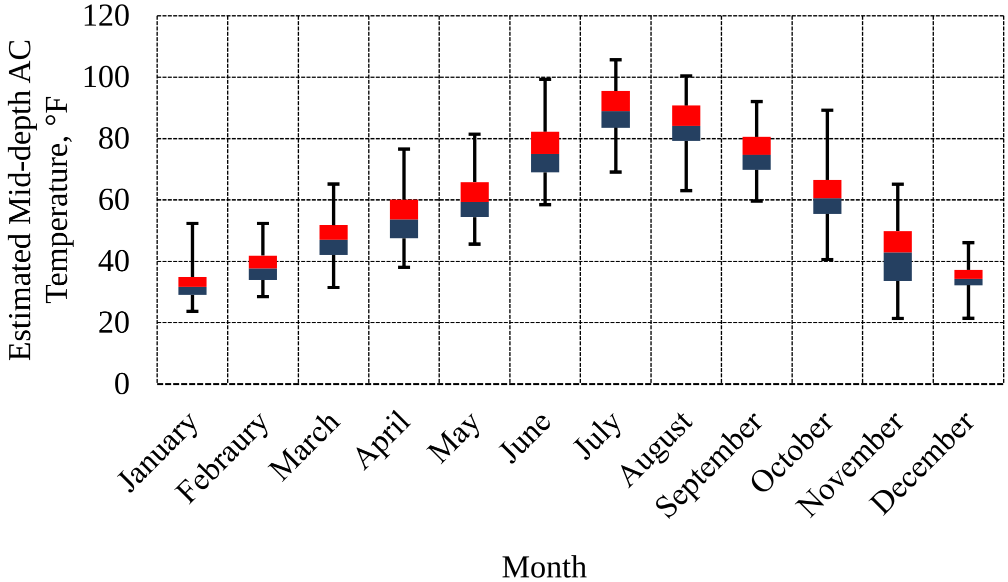


Figure A. 4: Estimated Mid-depth AC temperature for Lovelock station.

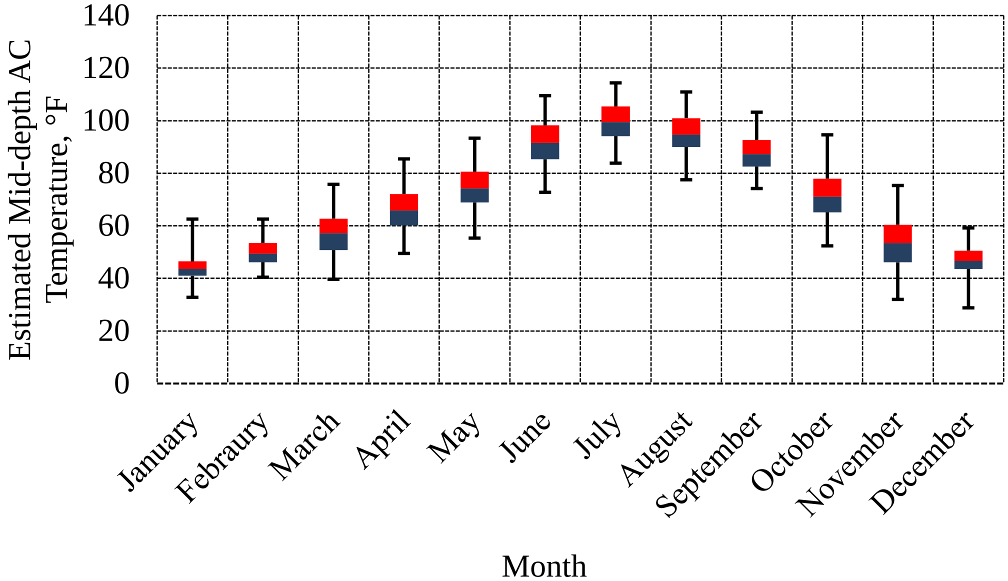


Figure A. 5: Estimated Mid-depth AC temperature for Mercury station.

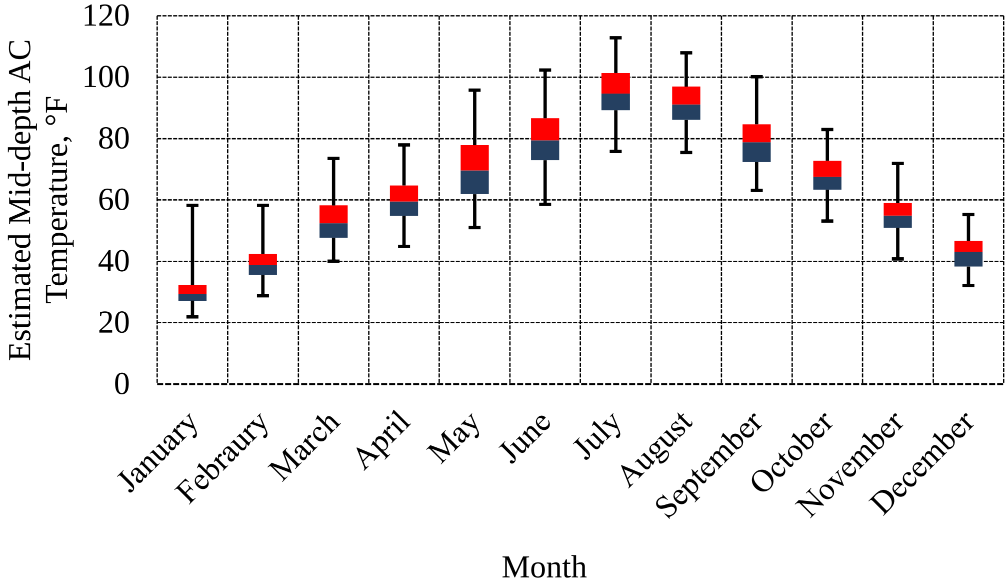


Figure A. 6: Estimated Mid-depth AC temperature for Reno station.

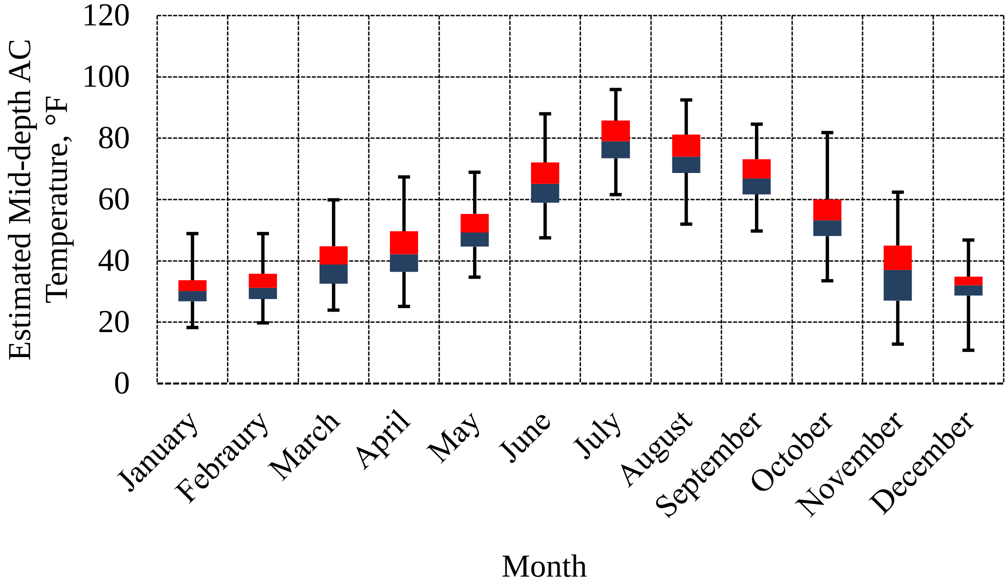


Figure A. 7: Estimated Mid-depth AC temperature for South Tahoe station.

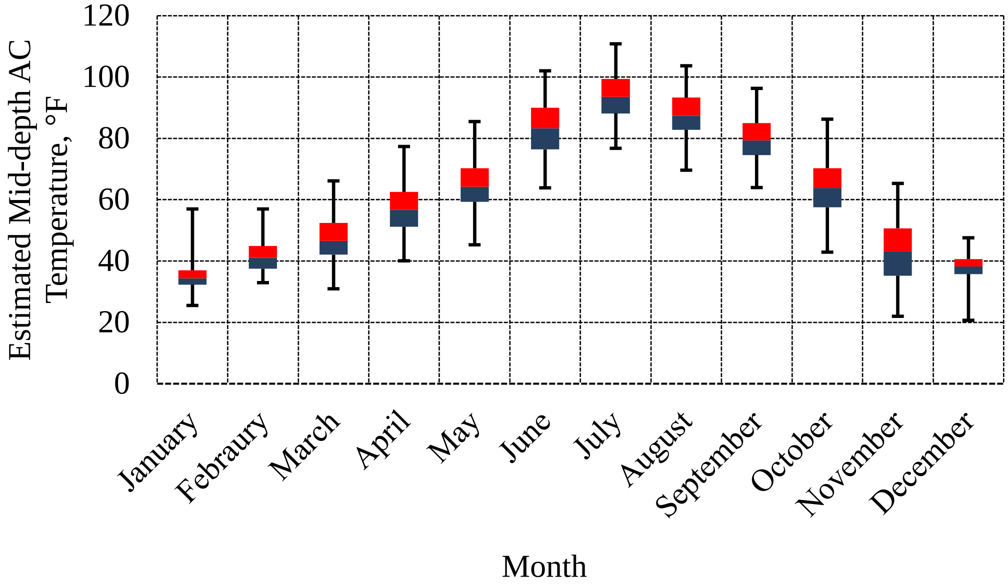


Figure A. 8: Estimated Mid-depth AC temperature for Tonopah station.

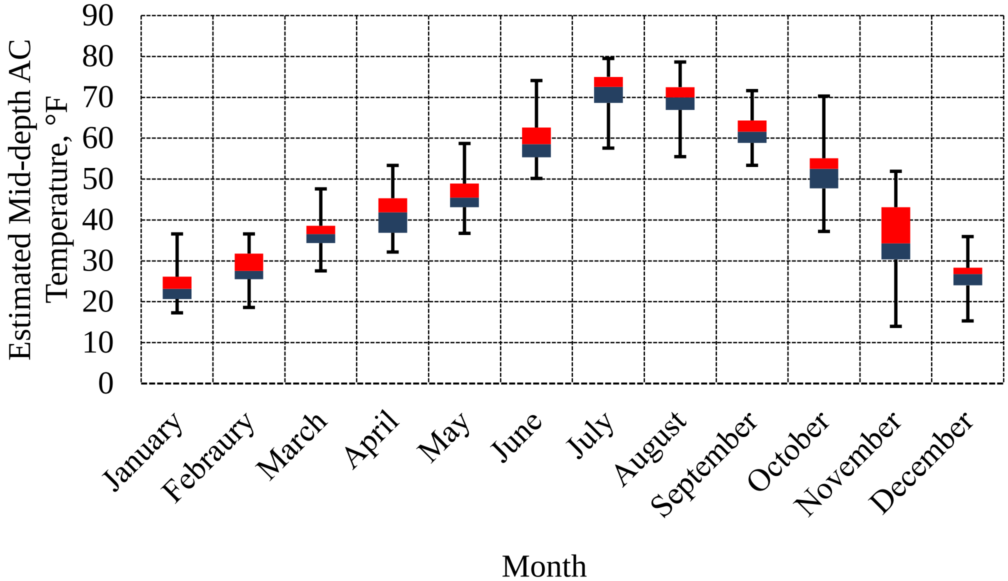


Figure A. 9: Estimated Mid-depth AC temperature for Winnemucca station.

APPENDIX B PDAC Output Results from Monte-Carlo Simulations

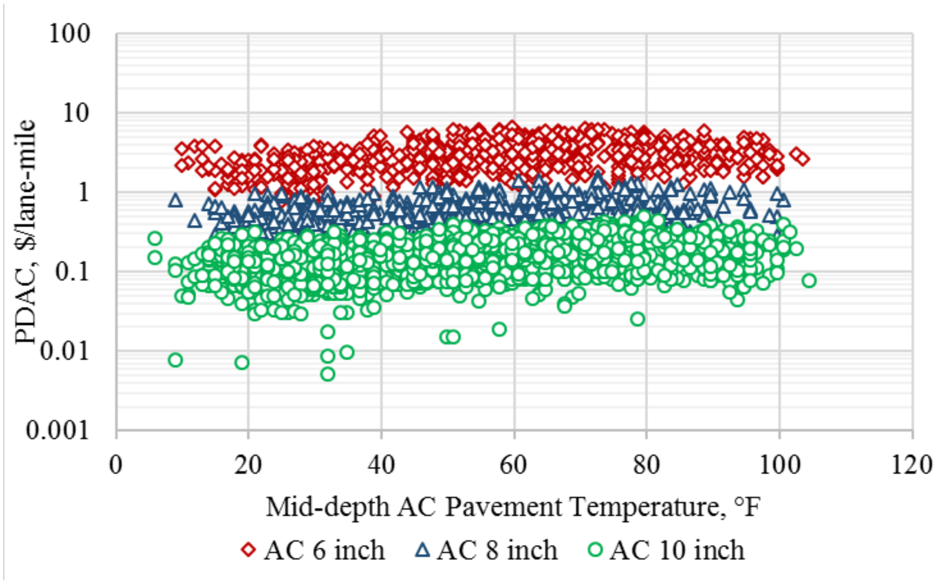


Figure B.1. Fatigue cracking based PDAC output from Monte-Carlo simulations for Elko weather station.

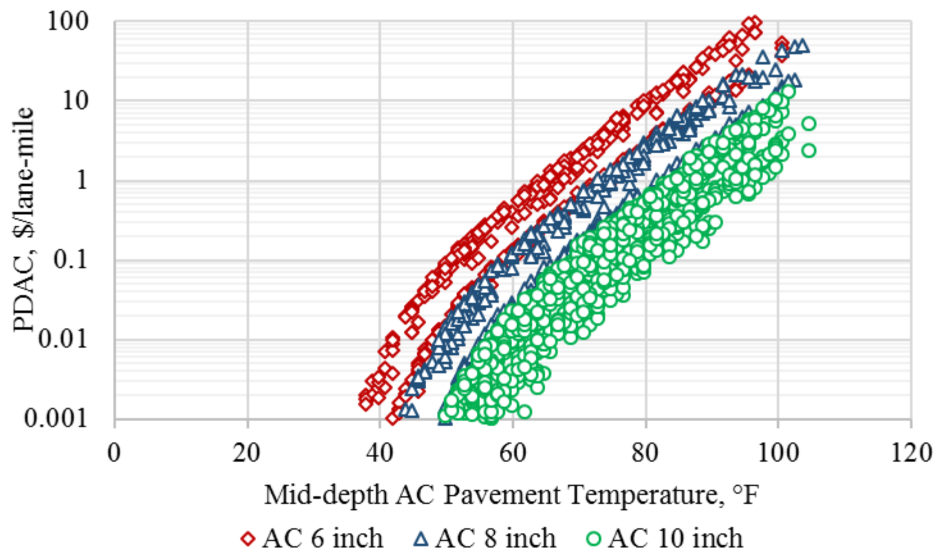


Figure B.2. AC permanent deformation based PDAC output from Monte-Carlo simulations for Elko weather station.

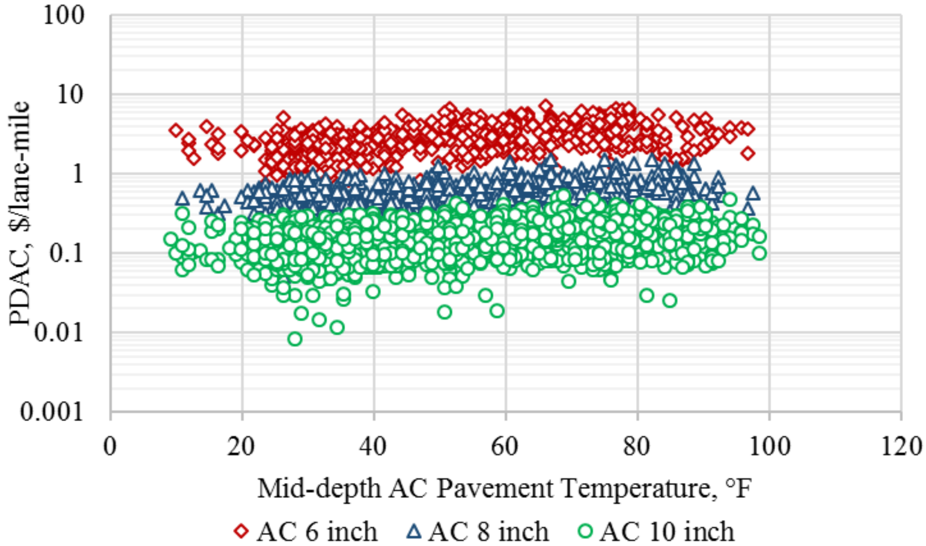


Figure B.3. Fatigue cracking based PDAC output from Monte-Carlo simulations for Ely weather station.

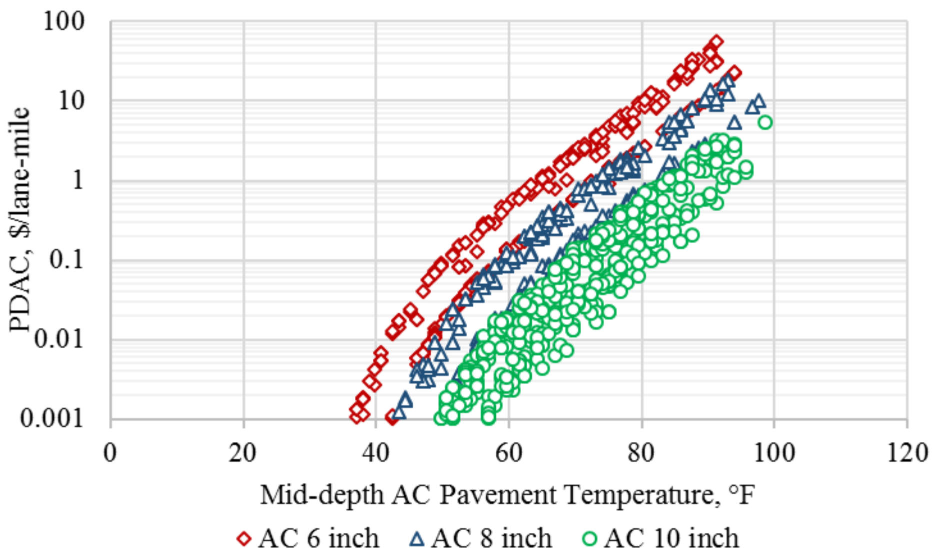


Figure B.4. AC permanent deformation based PDAC output from Monte-Carlo simulations for Ely weather station.

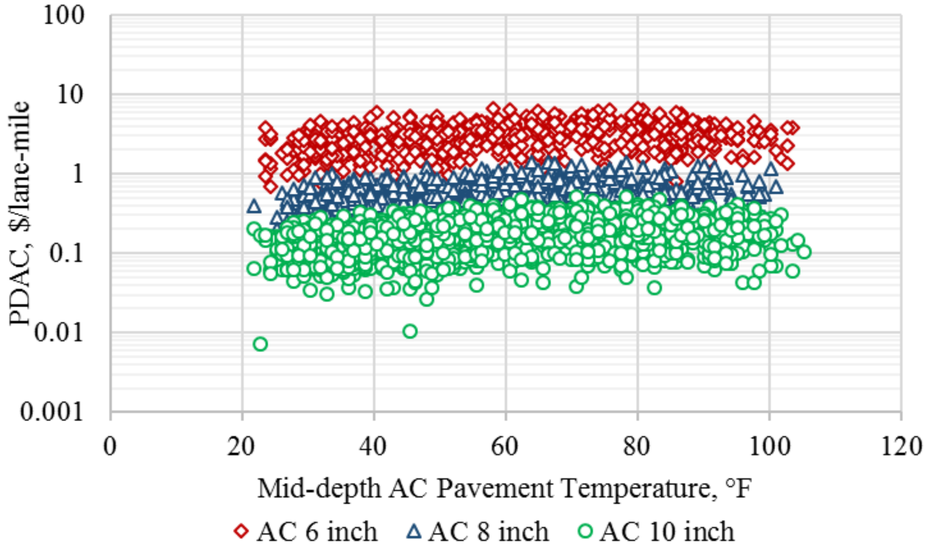


Figure B.5. Fatigue cracking based PDAC output from Monte-Carlo simulations for Lovelock weather station.

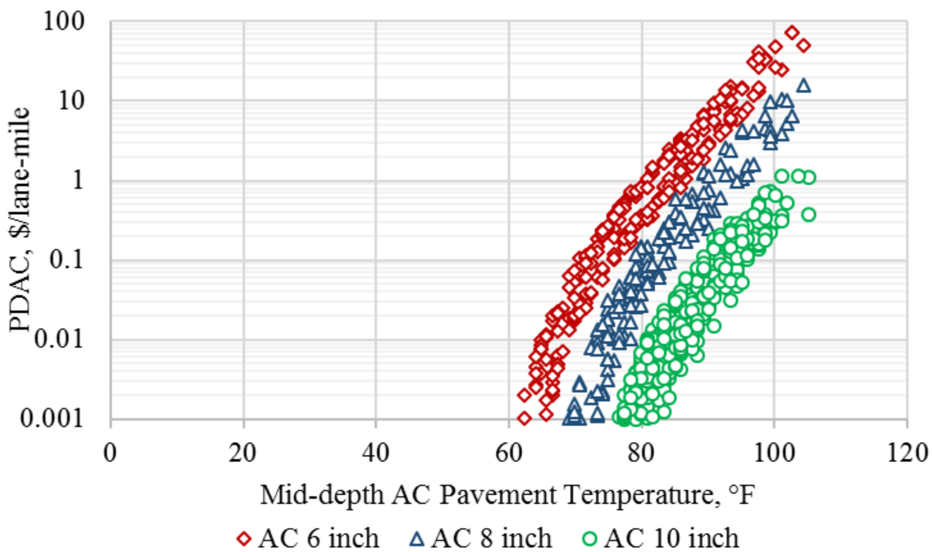


Figure B.6. AC permanent deformation based PDAC output from Monte-Carlo simulations for Lovelock weather station.

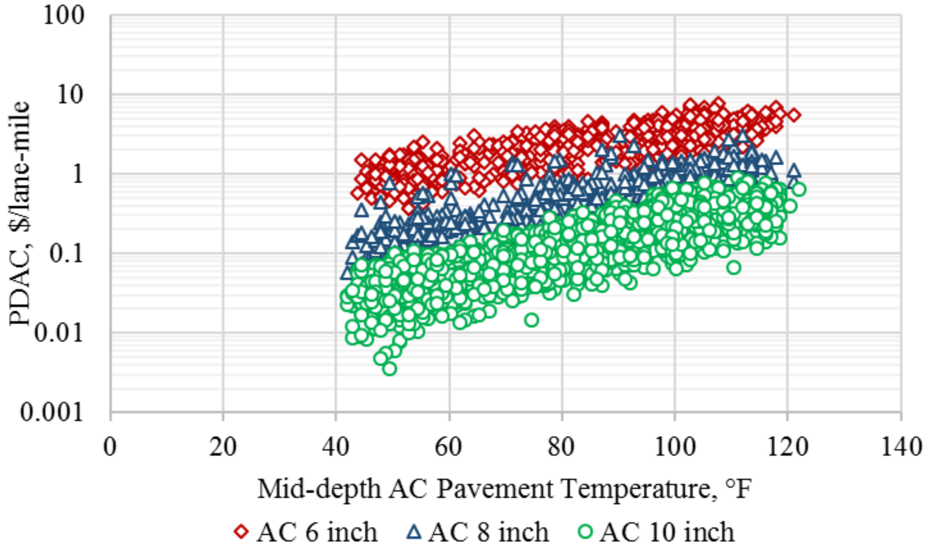


Figure B.7. Fatigue cracking based PDAC output from Monte-Carlo simulations for Las Vegas weather station.

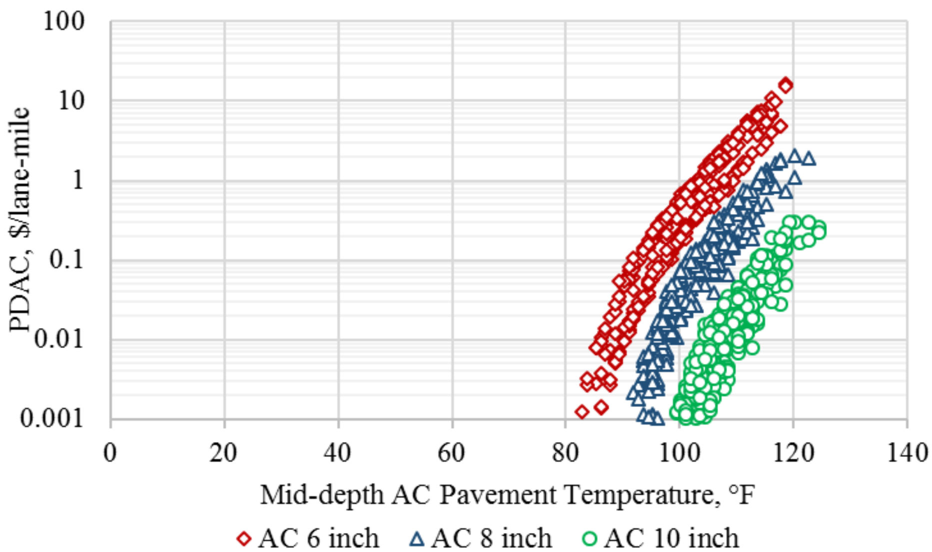


Figure B.8. AC permanent deformation based PDAC output from Monte-Carlo simulations for Las Vegas weather station.

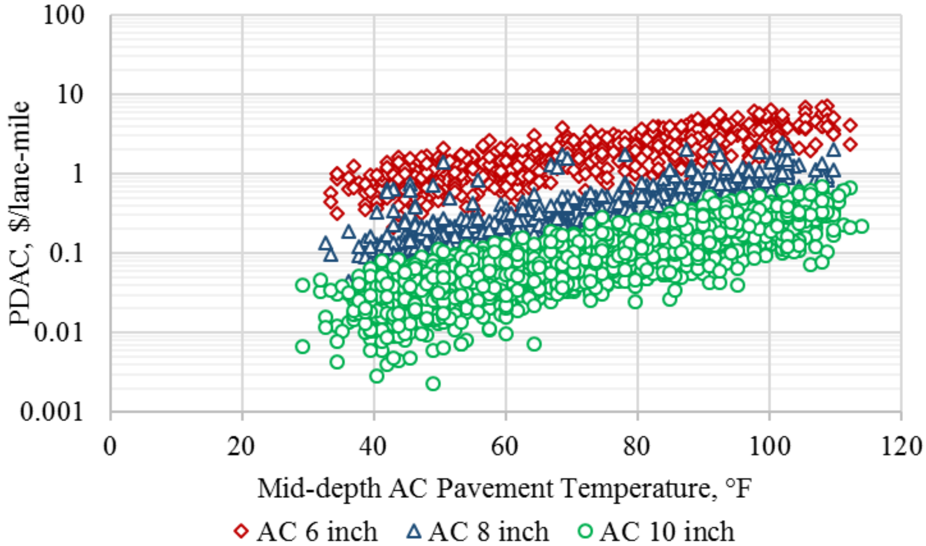


Figure B.9. Fatigue cracking based PDAC output from Monte-Carlo simulations for Mercury weather station.

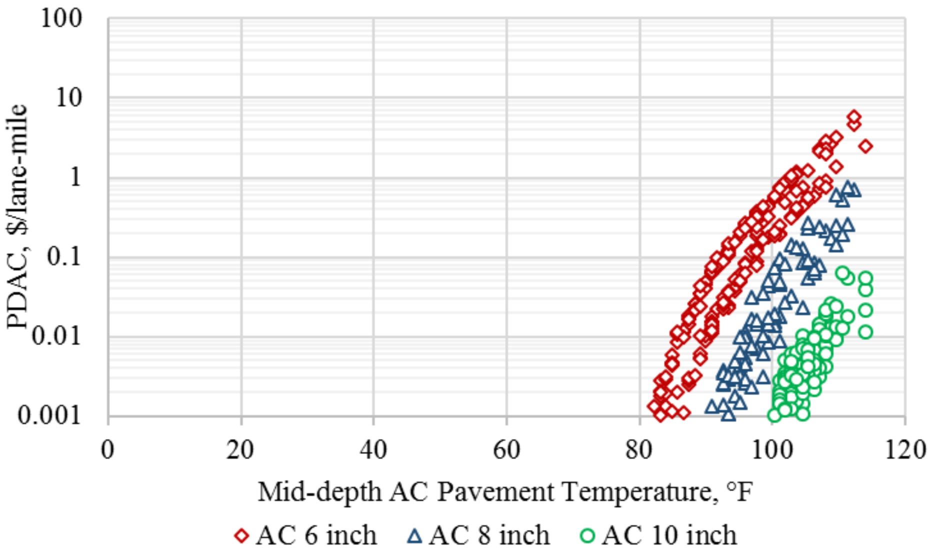


Figure B.10. AC permanent deformation based PDAC output from Monte-Carlo simulations for Mercury weather station.

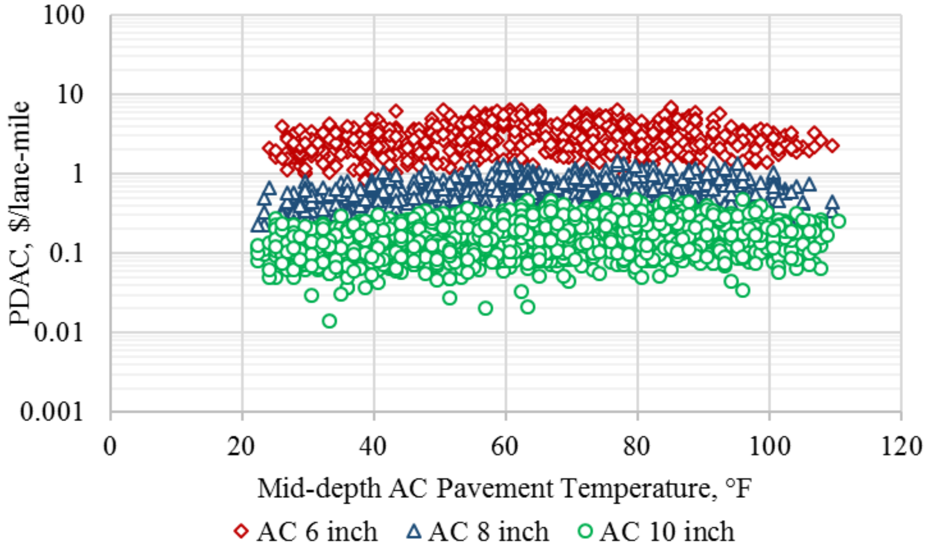


Figure B.11. Fatigue cracking based PDAC output from Monte-Carlo simulations for Reno weather station.

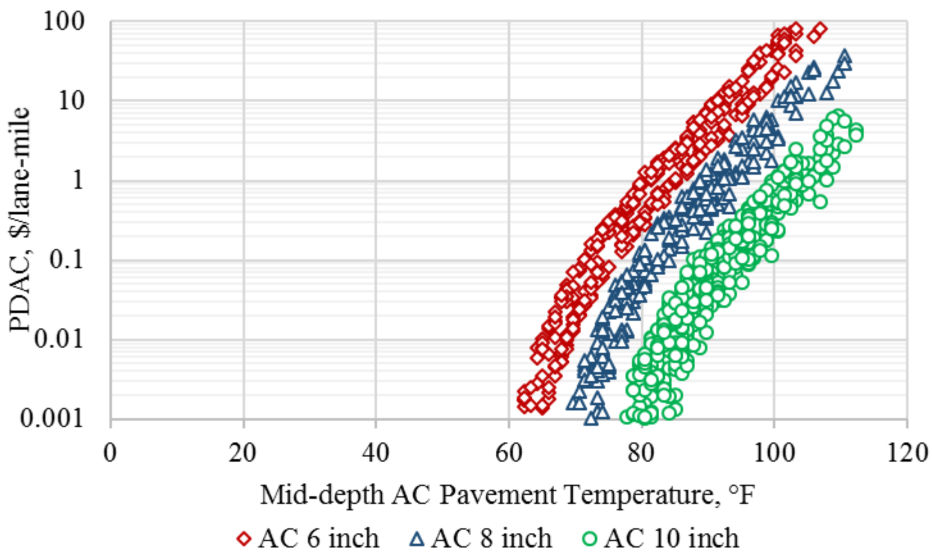


Figure B.12. AC permanent deformation based PDAC output from Monte-Carlo simulations for Reno weather station.

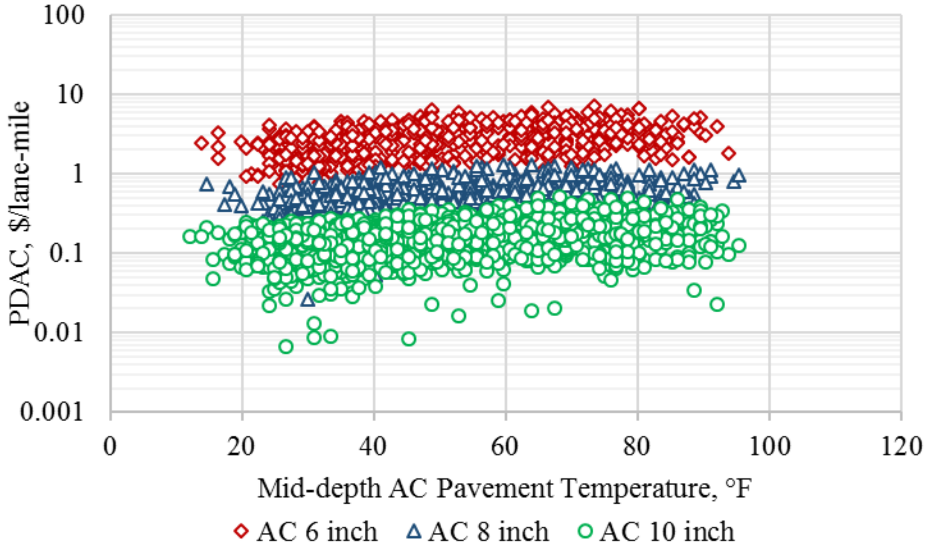


Figure B.13. Fatigue cracking based PDAC output from Monte-Carlo simulations for South Tahoe weather station.

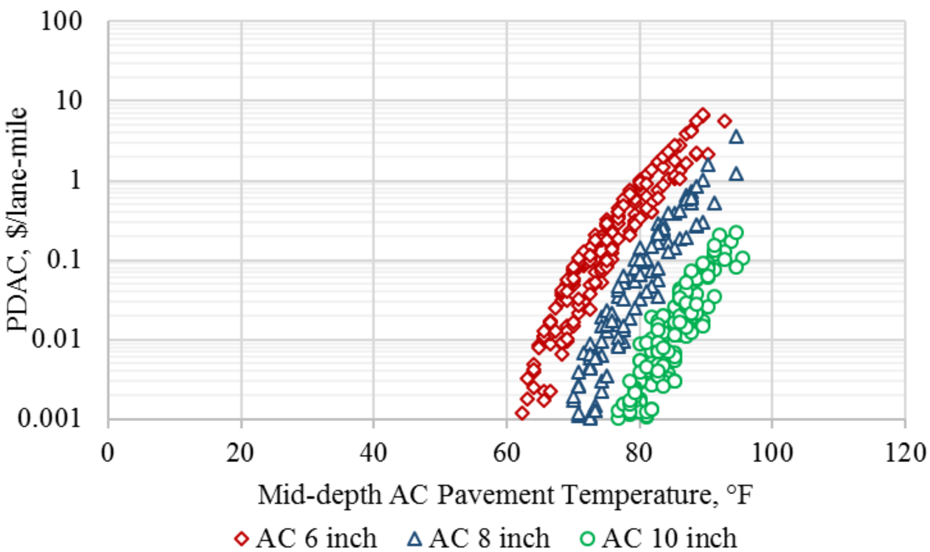


Figure B.14. AC permanent deformation based PDAC output from Monte-Carlo simulations for South Tahoe weather station.

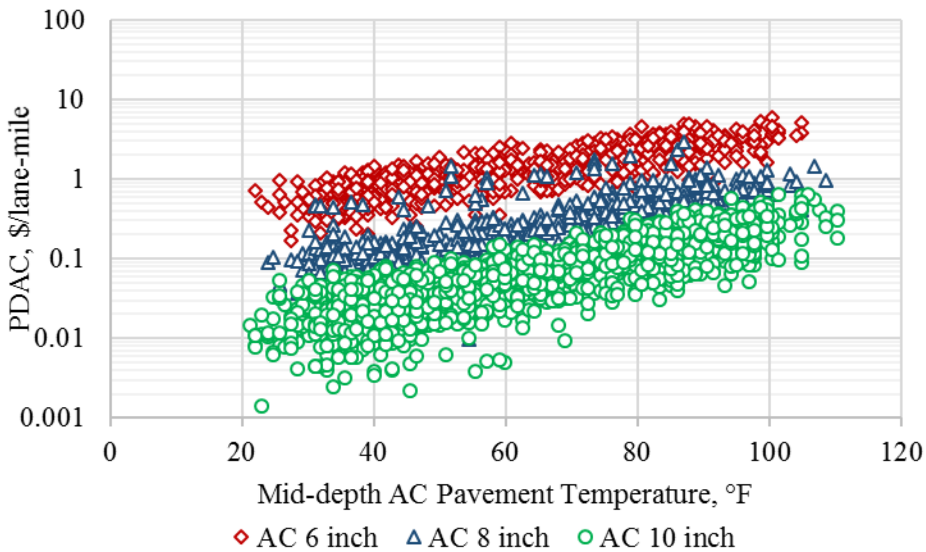


Figure B.15. Fatigue cracking based PDAC output from Monte-Carlo simulations for Tonopah weather station.

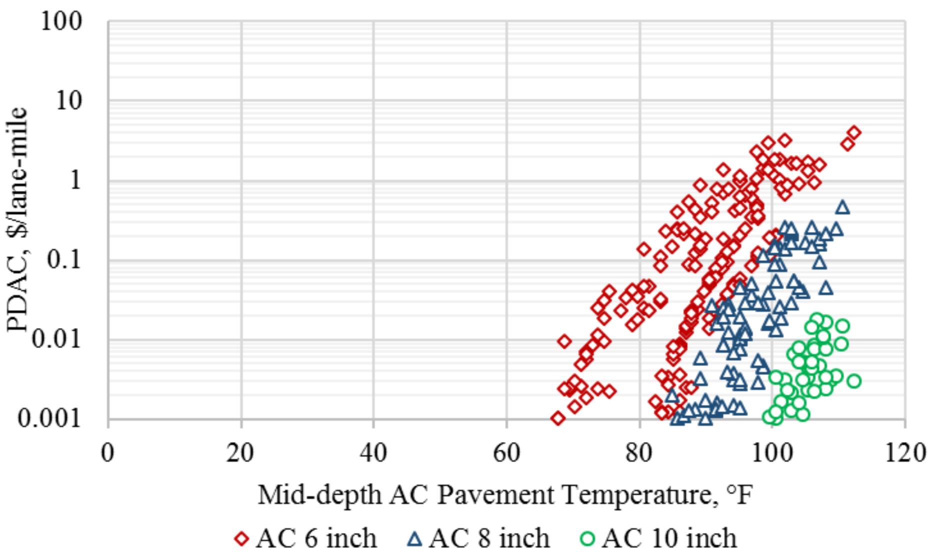


Figure B.16. AC permanent deformation based PDAC output from Monte-Carlo simulations for Tonopah weather station.

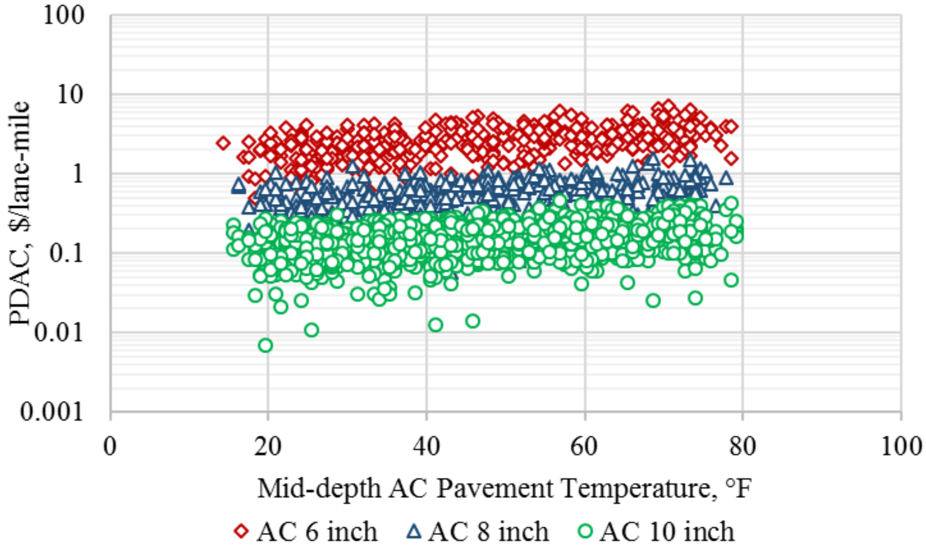


Figure B.17. Fatigue cracking based PDAC output from Monte-Carlo simulations for Winnemucca weather station.

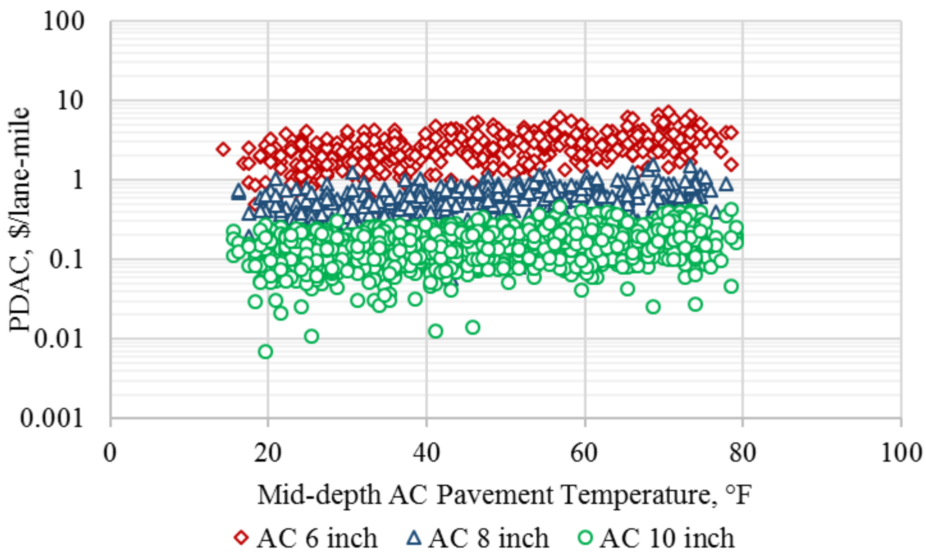


Figure B.18. AC permanent deformation based PDAC output from Monte-Carlo simulations for Winnemucca weather station.

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