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The assessment of damage to Texas highways due to oversize and overweight loads considering climatic factors

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ABSTRACT

Transportation agencies should have the capacity to evaluate the damage caused by oversize and overweight (OS/OW) vehicles in order to develop effective infrastructure management and rehabilitation strategies. In this paper, we discussed how to combine different paradigms that influence pavement performance into a single evaluation methodology by integrating the most available historical data with respect to the characteristics of OS/OW vehicles (i.e. dimension and weight), their origin and destination, permitted routes, frequency of the routes, pavement condition data, and climatic effects. The proposed methodology is then implemented into three case studies to indicate its applicability and practicality. In the case studies, we evaluate the impacts of OS/OW loads on pavements under different scenarios and combinations of the related factors. The corresponding relationships between pavement conditions and passing OS/OW loads are quantified with a well-accepted sigmoidal function. The results also indicate that, at the early age of the road, higher OS/OW loading would bring a faster deterioration rate (e.g. about 6\% of the reduction in service life for extreme high OS/OW loading, while only 2.35\% for low OS/OW loading). At the end of road life, the reduction trend slows down, nearly above 2\% for all OS/OW loading levels.

1. Background

In the state of Texas, trucks that carry loads more than standard weight limits (80,000 lbs.) and standard size (8 ft 6 in. wide and 14 ft high) are deemed as oversize and overweight (OS/OW) vehicles, and trucks with gross vehicle weight (GVW) exceeding 254,000 lbs. or maximum permissible weight on any axle or axle group, or 2,000,000 lbs. with less than 95 ft. of axle spacing is defined as a super heavy load (Lenz 2011). An OS/OW load can cause damage to highways in a number of ways. For example, an OS/OW load that exceeds the allowable limit can cause the damage to pavement including rutting, pavement edge failure, pavement surface failure, road embankment slope failure and pavement foundation shear failure. In the case of multiple super heavy loads (e.g. generated by wind turbine farms), the number of equivalent single axle loads (ESALs) may exceed the remaining life of the pavement. History has shown that it may only take one vehicle pass for such failures to occur (Fernando et al. 2006). In this regard, transportation agencies should have the capacity to estimate the impact of the damage caused by OS/OW vehicles in order to maintain the safety of the system and to develop effective infrastructure management and rehabilitation strategies.

The recent oil and gas booming produces over 546,000 jobs, generates $137.8 billion in economic output, and contributes more than $71.1 billion to the economy of Texas and New Mexico (Ewing et al. 2015). Accordingly, the number of OS/OW vehicles and the vehicle miles of travel (VMT) have increased rapidly over the past several years in Texas. The total number of OS/OW permits issued in FY 2014 was 836,259, which has increased 6 and 67\% over FY 2013 and FY 2010, respectively (Brewster 2013). However, development of the well site (i.e. the movement of equipment and materials necessary to construct the pad site and access roads), the drilling process (i.e. hydraulic fracturing) and operations (i.e. saltwater disposal) have brought high-volume and frequent truck trips and resulted in damage to state and county roads that were not designed for such traffic levels. Coordinated efforts towards efficient planning and routing of the OS/OW loads are becoming increasingly important from the standpoint of both pavement reservation and traffic management.

In this paper, we are describing the efforts of a research project sponsored by a regional University Transportation Center (UTC) in the U.S. Department of Transportation (DOT) Region 6. The project aimed to develop a web GIS-based routing assistance tool to optimise the OS/OW routes based on the historical and expected heavy traffic levels and pavement conditions. As one of the major project tasks, we evaluated the impact of OS/OW loads to highway pavements by analysing historical data with respect to the characteristics of OS/OW vehicles (i.e. dimension and weight), their origin and destination, permitted routes, frequency of the routes, pavement condition data, and climatic effects.
To the best knowledge of the authors, extensive studies have been made nationwide to develop load-zoning procedure and methods for evaluating load restrictions (Fernando et al. 2003, Banerjee and Prozzi 2015). These studies, however, did not lead to applicable methods that can be used to evaluate the impact of super heavy loads and to determine new design criteria and strategies for maintenance. There are no documented guidelines and recommendations that provide practical guidance on appropriate parameters (e.g. thickness and maximum repetition) and preservation techniques specifically developed for accommodation of the OS/OW loads. To this end, this paper has at least four major contributions: (1) conducting a comprehensive literature review on recent achievements of OS/OW studies; (2) finding the impact of different levels of OS/OW loads to highways considering climatic factors; (3) quantifying the parameters of the deterioration models for pavements under such circumstances for determining new design criteria and strategies to accommodate the OS/OW loads; and (4) the proposed approach is particularly valuable for the states with the GIS-based pavement management system that are looking for a workable solution to assess their mass historical OS/OW routing data, and to evaluate the OS/OW loading impact to infrastructures.

The rest of this paper is organised as follows: In Section 2, we conduct a comprehensive literature review on the OS/OW studies. In Section 3, we discuss the consolidation of the related data on pavement condition, OS/OW loadings, and climate zones from multiple well-established data sources. In Section 4, we describe the detailed procedures for modelling pavement performance. In Section 5, we design three case studies to evaluate the impact of OS/OW loads on highways in different scenarios and combinations of various factors. Section 6 concludes this paper with our major findings.

2. Literature review

In recent years, the State DOTs have witnessed a wave of increasing requests for OS/OW permits across the United States. These OS/OW traffic movements can disproportionately and negatively affect the integrity and quality of the pavement structure which was not designed to sustain routine overweight truck traffic. Since the potential for accelerated pavement deterioration exists, it is important that the State DOTs be able to estimate the impact and cost implications of the increasing numbers of OS/OW vehicles in order to manage their permit issuance practices, establish permit policies and procedures and devise weight enforcement strategies. Many research projects have been sponsored by the state DOTs to address their concern on the large number of OS/OW vehicles travelling over their road networks, including Indiana (Everett 2015), Texas (Li et al. 2012, Middleton et al. 2012, Banerjee and Prozzi 2015, Liu et al. 2016), Wisconsin (Owusu-Ababio and Schnitt 2005, Latifi 2014, Coley et al. 2016), Kansas (Bai et al. 2010), Virginia (VDOT 2008) and South Carolina (Dey et al. 2014), etc. These studies are mainly focused on the following areas: (a) Analysis of OS/OW routes based on the permit information; (b) Analysis of the effects of OS/OW traffic on pavements; (c) Analysis of OS/OW damage costs and permit fees; and (d) GIS tools for enhancing OS/OW administration.

2.1. Analysis of OS/OW routes based on the permit information

OS/OW permit programs allow carriers to move large, heavy and often high-value freight on state and federal highways. Generally, single-trip permits vehicles are issued by state DOTs for a specific vehicle and a specific one-way or return route, and vehicle dimensions, axle weights, and the planned route are recorded. By analysing the route descriptions from OS/OW permits, the researchers of this group can convert the available text information into route segments that could then be converted into route features in a geodatabase. This geodatabase could be used for the reconstruction of permitted OS/OW routes on a GIS-based state or federal highway system map. The outcomes of this research group can be used to visualise OS/OW routing trends, identify heavily travelled highway segments, and provide support for mechanistic-empirical pavement design guide (MEPDG) analyses and pavement reliability research (Coley et al. 2016). The results from this group are usually shared with other research groups to inform their studies.

Previous permit studies have often focused on case studies of individual load movements rather than using large-scale datasets of OS/OW permit information (Coley et al. 2016). In the recent years, researchers have changes their attentions on characterising OS/OW programs at a statewide level. The researchers from Texas were the pioneer in this field. They provided a first thorough analysis of permit vehicle characteristics in Texas as well as a geographic routing and origin–destination analysis (Li et al. 2012, Middleton et al. 2012). The study utilised a data-set from the Texas DOT that included 3,076,953 unique OS/OW permits over 6 years from 2004 to 2009. The results included maps of highway network utilisation by permit vehicles and also a density map of origin–destination pairs. The researchers from Wisconsin have performed a similar study for the WisDOT’s OS/OW program and the results was published in 2016 (Latifi 2014, Coley et al. 2016). In their study, the researchers developed a new methodology to map OS/OW permit vehicles, which used custom VBA scripts for text parsing and route processing with results linked to a GIS database. A large raw data-set of 784,759 axle-level records and 105,597 permit-level records from Wisconsin and a similar raw data-set of 43,337 single-trip overweight permits from Iowa were analysed by the proposed methodology. The GIS map of OS/OW routes built from their studies can be shared or used by other research groups such as our study.

2.2. Analysis of the effects of OS/OW traffic on roads

Traffic can be characterised by different types of vehicles with variations in load magnitude, the number of axles and the axle grouping. OS/OW vehicles can have all types of axles or some combinations of them, which accordingly have different influences on pavements. In this regard, analysing the effects of OS/OW traffic should account for their load magnitudes and axle configurations. A well-known method is to convert the passages of OS/OW vehicles into a number of passages of 18-kip (or 80-kN) single-axle loads using the load equivalent factor, known as the equivalent single-axle load (ESAL) methodology. The procedure of ESAL was first defined in the AASHTO Guide for Design of Pavement Structures, in which the load equivalent factor can be...
calculated as a function of the axle load and type of pavement structure (AASHTO 1993). Many researchers have applied the ESAL method to study the effects of OS/OW traffic on pavements. For example, Owusu-Ababio and Schmitt (2005) evaluated the impact of heavy loading concrete pavements along one logging truck corridor in Wisconsin. The results indicated that a high-end reliability combined with modified rigid ESAL factors has the potential to address overloading on Wisconsin’s concrete pavements (Owusu-Ababio and Schmitt 2005). Sadeghi and Fathali (2007) conducted sensitivity analysis to find the significant parameters that influence the deterioration of pavement under truck loading. The relationships between the truckloads and the number of allowable load cycles were obtained for each distress using the ESAL method (Sadeghi and Fathali 2007). The factors considered in the analysis include asphalt layer thickness, pavement temperature, subgrade condition and vehicle speed. Pais et al. (2013) studied the impact of traffic overload on road pavement performance using equivalent load factors. They found that the effect of vehicle loads was diminished by increasing the asphalt layer thickness, and subgrade stiffness had litter effect on the impact of vehicle loads, if the pavement distress is fatigue cracking (Pais et al. 2013). Gutekunst et al. (2016) used ESAL loadings to inspect and identify the critical road segments where damage from heavy truck traffic will occur and developed a tool that can help to prioritise pavement maintenance accordingly (Gutekunst et al. 2016).

Recently, the calculation of ESAL was moved from an empirical basis, such as the method proposed in the 1993 AASHTO guide, to a mechanistic-empirical approach (Ali 2005). Particularly in the OS/OW study, the researchers use the mechanistic model to study the physical heavy traffic impact on pavement structures and then calibrate them with observed empirical pavement performance from the field. For example, Wang et al. (2015) evaluated the impact of overweight traffic on pavement life using mechanistic-empirical analysis approach. The state of practice mechanistic-empirical pavement design and analysis software (Pavement-ME) was used to predict pavement life under different traffic loading scenarios. Field performance data at the sites where the weight-in-motion (WIM) data were collected were analysed to estimate the pavement service life at field condition (Wang et al. 2015). Other studies of this group can also be found in Hajj et al. (2016) and Freeman and Clark (2002).

2.3. Analysis of OS/OW damage costs and permit fees

Due to the damage imparted by OS/OW vehicles, the serviceability of pavements can prematurely fall below acceptable level, which requires more frequent maintenance and rehabilitation. To recover the costs of this accelerated deterioration, transportation agencies have been reviewing more efficient revenue sources to maintain their highway systems. In this regard, many research activities have been sponsored by the state DOTs to quantify the damage cost of OS/OW traffic on pavements and investigate the relative efficacy of different types of OS/OW permit fees (e.g. the flat per trip permit fee type, the axle-based permit fee type or the weight-based permit fee type, etc.). When deciding to implement one fee type over another or how more than one fee types could be combined, a trade-off analysis of fee types would provide useful information to policy-makers in selecting appropriate fee types to satisfy the OS/OW vehicle demand management goals (Dey et al. 2014). For example, Freeman and Clark (2002) conducted a study to determine the effect of higher allowable weight limit provisions on pavement maintenance and rehabilitation cost in Virginia (Freeman and Clark 2002). This study included traffic classification, weight surveys, an investigation of subsurface conditions and comprehensive structural evaluations. Bai et al. (2010) conducted a study to estimate the highway damage costs attributed to the truck traffic associated with the processed meat and related industries in Kansas. The researchers developed a systematic pavement damage estimation procedure that synthesised several existing methodologies including Highway Economic Requirements System (HERS) and AASHTO methods (Bai et al. 2010). A comprehensive overweight fee structure study was performed in Virginia. The authors recommended a two-part fee calculation method to determine appropriate permit fees to account for both pavement and bridge consumption (VDOT 2008). Dey et al. (2014) applied a damage quantification framework to estimate unit overweight truck damage costs for the highway system maintained by the South Carolina DOT. They conducted a comparative analysis between damage cost recovery fee types to provide insight to decision makers for setting policies regarding overweight trucking fees (Dey et al. 2014). Banerjee and Prozzi (2015) developed a practical approach for determining permit fees for overweight trucks based on consumption of service life of highways. The cost incurred in providing the additional structure to offset the accelerated consumption was assigned to the responsible truck fleet in proportion to the marginal load equivalency over the legal gross vehicle weight and axle weight tolerances (Banerjee and Prozzi 2015).

2.4. GIS tools for enhancing OS/OW administration

The state DOTs are issuing OS/OW permits and also are responsible for ensuring that all highways, bridges and other structures along the route can accommodate the physical size and weight characteristics of the vehicle. The permitting process is a complex procedure that involves route validation based on the size and weight of the permit vehicle and the constraints and conditions of specified routes. Pavement conditions, bridge clearances, bridge live load capabilities, roadway geometry and temporary restrictions are important in determining routing feasibility. Traditional methods for generating and validating vehicle routes are manual and thus labour intensive. Permit routes are usually traced by hand over paper or computer-generated maps. There exists a need for more user friendly tools to enhance OS/OW administration. Recently, Geographic Information System (GIS) have been proved as a promising tool for tackling this issue. For example, in 2007, TxDOT has introduced a new web-based tool called ’TxPROS’, which stands for Texas Permitting and Routing Optimization System, to enable self-permitting for OS/OW vehicles running over their road networks. The New York State DOT tool maintains up-to-date information about bridge clearances, bridge closures, bridge and highway weight restrictions, and other relevant routing information. Indiana DOT developed a GIS tool to determine the infrastructure consumption for individual permit records and administer overweight vehicle permits (Everett 2015). Liu et al. (2016) developed a web-based GIS routing assistance tool to evaluate and reduce OS/OW loads to highway pavements (Liu et al. 2016).
3. Data consolidation: pavement data, OS/OW routing data and climatic data

The evaluation of pavement damage caused by the OS/OW operation requires detailed information about pavement structures and materials, maintenance and repair (M&R) histories, OS/OW traffic characteristics, and regional climatic conditions. In the next subsections, we will discuss how to consolidate these related data from multiple well-established data sources.

3.1. Pavement management information system (PMIS) in Texas

The TxDOT maintains a vast network of highway pavements and has more paved lane-miles than any other state in the U.S. – 192,150 lane-miles to be exact. Effectively managing the required maintenance in order to preserve pavement assets with a limited budget has always been a challenge for Texas. Sufficient funds must be available to reconstruct and maintain pavements in the lane-miles that are nearing the end of the useful life. In addition, Texas’ role as a leading exporter, the continued growth of NAFTA traffic through state gateways, and the increased volume of shipping containers in the Gulf of Mexico due to the 2014 expansion of Panama Canal all combine to produce significant mobility needs between now and 2030 (Banerjee and Prozzi 2015). The programs that closely monitor the pavement network and effectively plan maintenance and rehabilitation (M&R) activities (with the corresponding budget limits) have becoming increasingly important to TxDOT. As a result, TxDOT has long been a proponent of pavement management systems (PMS) since their inception and implemented a comprehensive inventory and condition database for the entire state of Texas in the early 1990s (Zhang and Murphy 2013). The resulting database, termed Pavement Management Information System (PMIS) is still in use today and is updated annually with new data (Gharaibeh et al. 2012).

TxDOT divides each highway into a number of sections with an average length of 0.5 mile for pavement management and data collection purposes. Totally, more than 190,000 data collection sections are contained in PMIS, which are identified (or referenced) by a unique address – a combination of district name, county name, highway name, and beginning and end reference mile markers. In the PMIS database, pavement condition data are stored according to pavement type and its own distress types. For example, asphalt pavement has seven distress types (shallow rutting, deep rutting, patching, failures, block cracking, alligator cracking and longitudinal cracking). The percentage of the area or length of the section which is affected by each distress type is recorded as the density of that distress (Q). Q values can be converted to distress scores and additional information about this condition assessment method can be found in Gharaibeh et al. (2012). The Condition Score is a composite pavement performance index defined by TxDOT based on the combination of the Ride Score and the Distress Score. In a word, PMIS contains a wealth of pavement performance data that can be analysed and used to develop empirical performance prediction models.

In this study, we use PMIS as the major source for collecting the pavement data of the highways of interest. A request of PMIS data-set was initiated in March 2015 by the research team and was received from the TxDOT Lubbock District one month later. The data-set contains more than two million records that cover the state-wide network pavement data from 2004 to 2014.

3.2. The OS/OW routes in Texas

The characteristics of OS/OW vehicles such as dimensions and weights, origins and destinations (or the O-D matrix), permitted routes, and frequency of the routes are another kind of critical information. In this study, we used the OS/OW O-D map from a previous TxDOT research project (Middleton et al. 2012). Those researchers developed a highly efficient GIS-mapping approach and converted a massive data-set of OS/OW permit routes into a GIS format. The following procedures proposed by them can be summarised as follows:

- Clean and standardise the original route descriptions in TxDOT OS/OW permit data;
- Prepare a navigable route network based on a Texas DOT on-system roadway layer;
- Create a route intersection layer (referred to as the ‘junction layer’) that contained all intersections, origins and destinations involved in the original route descriptions;
- Map the route descriptions into separate ESRI shapefiles on the basis of the route layer and junction layer;
- Further process the resulting shapefiles for future GIS route analysis.

Figure 1 shows the most common roadways assigned to OS/OW loads in Texas.

3.3. Climate zones in Texas

Texas is the second largest state in the United States by population and area. It is located in the south central of the United States. Due to the large area, weather varies widely across Texas. The north Texas is cold and dry, while the south Texas is hot and humid. For the precipitation, El Paso, on the western end of the state, averages 8.7 inches (220 mm) of annual rainfall, while parts of south-east Texas average as much as 64 inches (1,600 mm) per year. Dallas in the North Central region averages a more moderate 37 inches (940 mm) per year. For the temperature, maximum temperatures in the summer months average from the 80 °F in the mountains of West Texas and on Galveston Island to around 100 °F in the Rio Grande Valley, but most areas of Texas see consistent summer high temperatures in the 90 °F range.

Temperature and moisture affect pavement performance, and hence its capacity to accommodate the OS/OW load. For example, the OS/OW load may cause pavement damage when it is transported at a time when the pavement is in a weakened state (e.g. soft asphalt concrete surface at high temperature and/or weak pavement soil foundation due to high moisture state). In this regard, we grouped pavement sections to represent the best-case and worst-case scenarios of these climatic characteristics, as follows:

- Zone 1: This zone represents dry–cold climate;
- Zone 2: This zone represents dry–warm climate;
- Zone 3: This zone represents wet–cold climate;
- Zone 4: This zone represents wet–warm climate;
Each county in Texas is assigned to one of the above zones and these zones are depicted in the colour-coded map shown in Figure 2. It should be noted that this climatic zone map is specially designed for the state of Texas. The classification of different zones may be not suitable for other states or areas.

4. Methodology: modelling pavement performance under multiple factors

In this study, we use Pavement Condition Score (PCS) as the primary performance index, which is a 1 – 100 index (with 100 representing no or minimal distress and roughness) defined by TxDOT in the PMIS. PCS considers pavement’s Distress Score (DS) and roughness (measured in International Roughness Index or IRI). These two indices can also be found in the PMIS database. According to PCS, roads can be grouped into five classes: Very Good (90–100), Good (70–89), Fair (50–69), Poor (35–49) and Very Poor (1–34) (Gharaibeh et al. 2012). A well-accepted sigmoidal function was used to regress pavement performance models under the combined effects of the aforementioned factors (Robinson et al. 1996, Mubaraki 2016, Wu et al. 2017):

\[
PCS = 100 \times \left(1 - e^{-\left(\frac{\text{Age}}{b}\right)^a}\right)
\]

where \(PCS\) = Pavement Condition Score defined by TxDOT, \(\text{Age}\) = Pavement Age, \(a\) and \(b\) are two coefficients that represent the effects of the considered factors.

Noted that the proposed model is not intended as a mechanistic explanation of the distress progression in pavements, but a most accurate regression possible with the available data.

Pavement age, construction and M&R histories are critical for the accuracy of the regression models, and, ultimately, for the confidence in these models. In a perfect data-set, PCS of
all sections in the network should stay constant or decrease with time. Otherwise, it should increase upon receiving a repair action. However, such a perfect data-set does not exist, since pavement condition data are noisy and contain errors (either human or systematic errors). In addition, even though the M&R data may be available, it is not easily accessible or ready for integration. M&R data are usually gathered by construction personnel and are stored in construction databases (separate from PMS database) (Saliminejad and Gharaibeh 2015). Integrating these data has always been a major challenge for TxDOT (Zhang et al. 2001). Thus, it is very difficult to integrate construction and repair history with condition data from these databases. To deal with noisy pavement condition data and integrate them with prior M&R histories, we used a method called ‘proximity-based outlier detection’ to group neighbouring roadway sections that have similar historical performance patterns (i.e. condition-versus-age patterns) (Saliminejad and Gharaibeh 2015). These proximity-based sections are likely to have similar characteristics (i.e. structure, climate, subgrade, traffic loading) and construction and repair histories. A group of these adjacent sections can be defined as a cluster.

The algorithm of clustering neighbouring pavement sections is discussed briefly here and more detail can be referred to the work of (Saliminejad and Gharaibeh 2012, 2015). In a cluster of pavement sections, the cluster’s homogeneity can be measured by the tightness of its probability density function (PDF), for example, the multivariate Gaussian PDF in Equation (2).

\[
f(x|\mu, \sigma^2) = \frac{1}{\sigma \sqrt{2\pi}} e^{-(x-\mu)^2 / 2\sigma^2} \quad (2)
\]

where \( f(x) \) is the probability density function and \( x = \text{PCS} \) in this case; \( \mu \) is mean of the PCS vectors for all pavement sections in the cluster; \( \sigma \) is standard deviation and \( \sigma^2 \) is variance; \( e \) is Euler’s number (\( e \approx 2.71828 \)).

The optimal clustering scenario can be determined by searching the scenario that maximises the overall probability of pavement sections belonging to clusters. In mathematical terms, the probability that a highway consists of a clustering scheme \( (g_1, \ldots, g_k) \), given that the condition data for \( n \) sections in this highway are \( \text{PCS}_1 \) to \( \text{PCS}_n \), can be computed as follows:

\[
P(g_1, \ldots, g_k|\text{PCS}_1, \ldots, \text{PCS}_n) \propto \prod_{i=1}^{n} P(\text{PCS}_i|g_1, \ldots, g_k) \prod_{j=1}^{k} P(g_j) \quad (3)
\]

where \( P(g_j) \) is the probability of having an M&R project with the length equal to \( g_j \); \( P(\text{PCS}_i|g_1, \ldots, g_k) \) is the probability of having a condition data vector of \( \text{PCS} \) for section \( i \), given the clustering scheme \( g_1, \ldots, g_k \).

Among all possible clustering scenarios, the one gives the highest probability (calculated by Equation (4)) is selected as the optimum clustering scenario. A genetic algorithm (GA) is used to solve this clustering problem because of its computational efficiency in finding a near-optimal solution for the fitness function (i.e. Equation (3)) and its lack of sensitivity to initial values (Ashlock 2006). Finally, each highway corridor in the network can be segmented into homogeneous clusters consisting of the pavement sections with similar construction and repair actions.

After clustering pavement sections, it is necessary to estimate pavement age based on performance data and historical M&R information. Year of M&R treatment can be estimated based on the magnitude of increase in PCS and the year in which this increase occurred. For example, considering a pavement section, its PCS was 100 at 2010 and then gradually decreased to 35 in 2013. Then the value of PCS has suddenly increased from 35 to 100 in 2014. Thus, it can be assumed that this pavement section received a major rehabilitation in 2013 (making its age in 2013 is 4 years and in 2010 is 0 years). Once condition-versus-age patterns are determined, the pavement performance curve can be regressed and the related coefficients (i.e. parameters \( a \) and \( b \) in Equation (1)) can be determined finally. The proposed pavement performance models and the data grouping algorithm will be discussed in more detail in the following case study section.

5. Case study: the impact of OS/OW loads on highways in different Texas climate zones

As discussed previously, to evaluate the impact of OS/OW loads on highways in different climate zones, multiple factors need to be considered, i.e. pavement characteristics, climate, subgrade quality, OS/OW traffic loading levels, maintenance and rehabilitation historical activities. Thus, in this section, we designed three case studies to evaluate pavement performance in different OS/OW scenarios and combinations of the related factors. In case study 1, we only considered the highways with the same OS/OW loading level, but in different climate zones. In case study 2, we put our focus on the highways in one climate zone only (i.e. Zone 2 in this case) and studied their performance at various OS/OW traffic levels. In case study 3, we made a further analysis on the reduction of pavement service life for the highways selected in case study 2. Noted that pavement age and the M&R history are two key variables in the whole regression process. The regression procedures are illustrated in Figure 3 for the purpose of better understanding. The details of three case studies are being elaborated in the following subsections.

5.1. Case study 1: the impact of OS/OW vehicles on highways in different climate zones

In this case study, we designed two scenarios: the high OS/OW traffic scenario (greater than 5000 permits for OS/OW vehicles per year) and the low OS/OW traffic scenario (less than 500 permits for OS/OW vehicles per year). In each scenario, based on the Texas OS/OW vehicles routing map (as shown in Figure 1), we selected representative highways as the objects of regression analysis. Next, we applied the proposed methodology with the associated pavement condition data, and then obtained the regression curves for the selected highways. It should be noted that, for the comparative purpose, we selected highways in the same road classification, wherever possible, if the data permits. Results and findings from the two scenarios will be discussed in detail as follows.

- The high OS/OW traffic scenario

In this scenario, we selected one highway in each climate zone, which are: US287L (Zone 1), US287L (Zone 2), US90R (Zone 3),
Zone 1 reduced from 100 to 85 in less than two years). The reasons are twofold: the high level of OS/OW loads and none or minimal repair interventions scheduled in the early age of pavement. The reduction speed in pavement performance for four climate zones (as measured by PCS) shows the following trend:

- In a long-term period (i.e. pavement age is more than five years), the reduction speed in pavement performance for four climate zones shows a different trend:

  - It is reasonable to observe different trends in pavement performance since we take the prior M&R history as a critical variable in the regression process. Thus, the regression curves reflect the combined effects of pavement age-

- The low OS/OW traffic scenario

  In this scenario, similarly, we still selected one road in each climate zone, which are US77L (Zone 4). Noted the selected roads are in the same classification to ensure that they have similar pavement characteristics (materials and structures, for example) at the maximum extent. Their pavement performance curves were regressed, as shown in Figure 4. The regression coefficients are summarised in Table 1. We have the following interesting findings:

  - In a short-term period (i.e. pavement age is less than two years), the PCS of the selected highways dropped drastically (i.e. in the worst case, the PCS of the Highway in

  - Zone 1 > Zone 3 > Zone 4 > Zone 2

  - In a long-term period (i.e. pavement age is more than five years), the reduction speed in pavement performance for four climate zones shows a different trend:

  - Zone 3 > Zone 4 > Zone 1 > Zone 2

  - It is reasonable to observe different trends in pavement performance since we take the prior M&R history as a critical variable in the regression process. Thus, the regression curves reflect the combined effects of pavement ageing, OS/OW traffic loads and M&R interventions.

- The low OS/OW traffic scenario

  In this scenario, similarly, we still selected one road in each climate zone, which are US70L (Zone 1), US62L (Zone 2), US90L (Zone 3), FM2686K (Zone 4). It should be noted that in Zone 4, we chose an FM class road due to the limited data. Their pavement performance curves were regressed, as shown in Figure 5. The regression coefficients are also summarised in Table 1. We have the following interesting findings as observed from Figure 5:
This trend is consistent with our logical understanding about the climatic effects on pavement: without implementing any M&R interventions at the early age of pavement, pavements in cold and dry weather have a better performance than those in warm and wet weather.

• In a long-term period (i.e. pavement age is more than four years in this case), the roads present various trends in pavement performance reduction. It is reasonable since M&R actions will be implemented on pavement as time goes and our regression models take the prior M&R history as the critical variable. In other words, the observed trends present the combined effects of M&R actions and climatic effects on the pavement later age behaviour.

• It should be noted that the performance of roads in this scenario has dropped much more than the roads in the first scenario in the whole service life (20 years in this case). It is reasonable since we consider the effects of prior M&R activities in our regression models. Normally, the DOTs pay more attentions on the roads with high OS/OW traffic loads and implement more frequent M&R actions. In this regard, the pavement performance of these roads can be maintained well and their PCS are usually kept at a higher level during the whole service life. Especially, the Texas Transportation Commission’s stated goal is to reach 90 per cent ‘good’ or better pavement conditions, which means the PCS and Distress of a road need to be at least ’70’ or up.

5.2. Case study 2: the impact of OS/OW vehicles on highways in the same climate zone

In this case study, we put our focus on Zone 2 only and studied the roads with different levels of OS/OW loads in the same climate zone. We divided the OS/OW loading into three levels: High (between 200,000 and 1,000,000 ESALs per year), Medium (between 20,000 and 200,000 ESALs per year) and Low (less than 20,000 ESALs per year). Next, we selected one road at each level, which are: US287L (High), US180L (Medium), US62L (Low). Noted the selected roads are in the same class to ensure that they have similar pavement characteristics (materials and structures, for example) at the maximum extent. The performance curves of these roads were regressed and illustrated in Figure 6. The regression coefficients are summarised in Table 2. We have some interesting findings as follows:

• In a short-term period (i.e. pavement age is less than four years in this case), the reduction speed in pavement performance (as measured by PCS) shows the following trend:

   Zone 4 > Zone 3 > Zone 2 > Zone 1

• In a long-term period (i.e. pavement age is more than four years in this case), the reduction speed presents an opposite trend:

   High OS/OW Loading
   > Medium OS/OW Loading > Low OS/OW Loading

   High OS/OW Loading
   < Medium OS/OW Loading < Low OS/OW Loading

### Table 1. The regression coefficients for two scenarios in case study 1.

<table>
<thead>
<tr>
<th>Case Study</th>
<th>Climate zone</th>
<th>Selected road</th>
<th>Road sections</th>
<th>Parameter a</th>
<th>Parameter b</th>
</tr>
</thead>
<tbody>
<tr>
<td>The high</td>
<td>Zone1</td>
<td>US287L</td>
<td>122-278</td>
<td>15,673.0012</td>
<td>0.0651</td>
</tr>
<tr>
<td>OS/OW</td>
<td>Zone2</td>
<td>US287L</td>
<td>278-394</td>
<td>5254.8034</td>
<td>0.0939</td>
</tr>
<tr>
<td>loading</td>
<td>Zone3</td>
<td>US90R</td>
<td>692-922</td>
<td>35.0625</td>
<td>0.2000</td>
</tr>
<tr>
<td>scenario</td>
<td>Zone4</td>
<td>US77L</td>
<td>710-814</td>
<td>50.6585</td>
<td>0.2057</td>
</tr>
<tr>
<td>The low</td>
<td>Zone1</td>
<td>US70L</td>
<td>226-480</td>
<td>8.4662</td>
<td>0.9087</td>
</tr>
<tr>
<td>OS/OW</td>
<td>Zone2</td>
<td>US62L</td>
<td>24-136</td>
<td>6.8977</td>
<td>0.9450</td>
</tr>
<tr>
<td>loading</td>
<td>Zone3</td>
<td>US90L</td>
<td>422-484</td>
<td>7.4720</td>
<td>0.7123</td>
</tr>
<tr>
<td>scenario</td>
<td>Zone4</td>
<td>FM2686K</td>
<td>474-492</td>
<td>6.4260</td>
<td>0.6912</td>
</tr>
</tbody>
</table>
It is reasonable since we consider the prior M&R history as the key factor in our regression model. It is obviously that the road that transport high volumes of OS/OW vehicles is usually implemented more frequent M&R actions than the one with low OS/OW loading. Thus, the highway in high loading level has maintained a high-level pavement condition throughout its whole service life (take US 287 as an example, its PCS is higher than 80 at the end of its service life). Correspondingly, the pavement performance of low-level highway has dropped drastically during its whole service life (take US 62 as an example, its PCS is less than 25 at the end of its service life).

### 5.3. Case study 3: the pavement service life reduction at various OS/OW loading levels

In this case study, we made a further analysis to investigate the pavement service life reduction at various OS/OW loading levels. Noted that the OS/OW load level on a highway is measured by accumulative ESALs. In this case, we divided the OS/OW loading into four levels:

- Super high OS/OW Loading: greater than 1,000,000 ESALs per year,
- High OS/OW Loading: between 200,000 and 1,000,000 ESALs per year,
- Medium OS/OW Loading: between 200,000 and 200,000 ESALs per year,
- Low OS/OW Loading: less than 20,000 ESALs per year.

Correspondingly, we selected four highways based on the Texas OS/OW vehicle routing map, which are: US 337 (Low), US 62 (Medium), US 67 (High) and US 180 (Extreme). Letting $\Delta$Life (%) denote the road service life reduction percentage. For example, $\Delta$Life (%) is equal to 0% for a new road (or the road service life is 100% at this point). As time goes by, the accumulative ESALs on this road will be increased, and so will the reduction of service life ($\Delta$Life (%)). We chose a basic exponential function to regress the relationship between the pavement service life reduction versus pavement age, as shown in Equation (4):

\[ \Delta \text{Life}(\%) = a \times (\text{Accumulative ESAL})^b + c \]  

where $a$, $b$, and $c$ are regression coefficients that we need to find.

In Figure 7, the upper figure presents the road service life reduction measured in ΔPCS %, while the lower one shows the rate of service life reduction measured in ΔPCS%/ESAL. Noted that the reduction rate can be easily obtained by taking the first derivative of Equation (4).

The regression curves in the upper figure present a clear trend of the pavement service life reduction under various levels of OS/OW loading:

\[ \Delta \text{Life}(\%) \text{ (Super High)} > \Delta \text{ Life}(\%) \text{ (High)} > \Delta \text{ Life}(\%) \text{ (Medium)} > \Delta \text{ Life}(\%) \text{ (Low)} \]

The observed trend is consistent with our logical expectation: the more OS/OW loads, the more pavement damage and hence the more reduction of pavement service life. More specially, in this case, when the accumulative ESAL is 10 million, the service life reduction is 35, 26, 22 and 18% for the roads with extreme, high, medium and low OS/OW loads, respectively. We also further quantified the service life reduction by the following equations:

\[ \Delta \text{Life}(\%) = 9.599 \times (\text{A_ESAL})^{0.6074} - 3.581 \text{ (Super High)} \]  
\[ \Delta \text{Life}(\%) = 5.043 \times (\text{A_ESAL})^{0.7781} - 3.581 \text{ (High)} \]  
\[ \Delta \text{Life}(\%) = 3.6671 \times (\text{A_ESAL})^{0.8390} - 3.581 \text{ (Medium)} \]  
\[ \Delta \text{Life}(\%) = 2.422 \times (\text{A_ESAL})^{0.9694} - 6.206 \text{ (Low)} \]

The curves in the lower figure present the service reduction rates by taking the first derivative of the above equations. The results show that at the early age of the road, higher OS/OW loads would bring a faster deterioration rate. For example, when the accumulative ESAL is equal to two million, the service life reduction rates are 5.83, 3.92, 3.08 and 2.35%, for the extreme, high, medium and low ESAL scenarios, respectively. While, in the long term or at the end of road life (e.g. the accumulative ESAL = 20 million), the reduction trend slows down and the reduction rates are nearly 2% for all of four scenarios. This observation is also consistent with other pavement performance studies and suggests that applying preventative maintenance at the early age of pavement may extend the road's service life to the maximum extent. The service reduction rates are also quantified by the following equations:

\[ \Delta (\Delta \text{Life}(\%)) = 5.8304 \times (\text{A_ESAL})^{-0.3926} \text{ (Super High)} \]  
\[ \Delta (\Delta \text{Life}(\%)) = 3.9240 \times (\text{A_ESAL})^{-0.2219} \text{ (High)} \]  
\[ \Delta (\Delta \text{Life}(\%)) = 3.0767 \times (\text{A_ESAL})^{-0.1610} \text{ (Medium)} \]  
\[ \Delta (\Delta \text{Life}(\%)) = 2.3479 \times (\text{A_ESAL})^{-0.0306} \text{ (Low)} \]

### 5.4. Validation

In this section, we will discuss how the developed deterioration models can be validated. When building the models, for the road sections selected, we used the even-numbered sections to build the regression models, while keeping the odd-numbered sections to validate them. If we take the high OS/OW traffic scenarios in case study 1 as an example here. The validation results are shown in Figure 8 below. The values of root-mean-square-error (RMSE) between the models and the field data are 0.66087, 0.38661, 0.41144 and 0.273 for Zone 1, Zone 2, Zone 3 and Zone 4, respectively. The figure and the RMSE values indicated that our models are well consistent with the field data.
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used a method called ‘proximity-based outlier detection’ to group neighbouring roadway sections that have similar historical performance patterns (i.e. condition-versus-age patterns).

Lastly, we designed three case studies to evaluate highway pavement performance in different OS/OW scenarios and combinations of the related factors. In the first case study, we investigated the impacts of OS/OW vehicles on highways in different climate zones. In the second case study, we studied the pavement performance at different levels of OS/OW loads in the same climate zone. In the third case study, we made a further analysis to investigate the pavement service life reduction at various OS/OW loading levels. The regression curves, the regression coefficients and the related findings were elaborated in the case study section.

The major findings are summarised as follows:

• The impact of OS/OW loads on roads in different climate zones:
  ◦ In a short-term period, without implementing any M&R interventions at the early age of pavement, pavements in cold and dry weather have a better performance than those in warm and wet weather.
  ◦ In a long-term period, roads present mixed trends in pavement performance reduction for different climate zones. It is reasonable since M&R actions will be implemented on pavement as time goes and our regression models take the prior M&R history as the critical variable. In other words, the observed trends present the combined effects

Similarly, the validation results for the low OS/OW traffic scenarios in case study 1 and the scenarios in case study 2 can be found in Figures 9 and 10, respectively.

6. Conclusions and future work

In this paper, we present the work of a US DOT research project which is aimed to develop a web GIS-based routing assistance tool to optimise the OS/OW routes based on the historical and expected heavy traffic level and pavement condition. We put our focus on discussing one of the major tasks of this project: evaluating the impact of OS/OW loads to highway pavements by analysing historical data with respect to the characteristics of OS/OW vehicles (i.e. dimension and weight), their origin and destination, permitted routes, frequency of the routes, pavement condition data, and climatic effects.

To accomplish this task, firstly, we consolidated various datasets from multiple well-known databases or previous research projects to obtain the related pavement data and the OS/OW loading data. Secondly, to represent the most accurate regression possible with the available data, we used a well-accepted sigmoidal function and a basic power function to develop pavement performance models under the combined effects of the aforementioned factors. In the regression modelling process, pavement age and the prior M&R history are redeemed as two critical parameters. In the regressing process, to deal with noisy pavement condition data and integrate them with prior M&R histories, we used a method called ‘proximity-based outlier detection’ to group neighbouring roadway sections that have similar historical performance patterns (i.e. condition-versus-age patterns).

Lastly, we designed three case studies to evaluate highway pavement performance in different OS/OW scenarios and combinations of the related factors. In the first case study, we investigated the impacts of OS/OW vehicles on highways in different climate zones. In the second case study, we studied the pavement performance at different levels of OS/OW loads in the same climate zone. In the third case study, we made a further analysis to investigate the pavement service life reduction at various OS/OW loading levels. The regression curves, the regression coefficients and the related findings were elaborated in the case study section. The major findings are summarised as follows:

• The impact of OS/OW loads on roads in different climate zones:
  ◦ In a short-term period, without implementing any M&R interventions at the early age of pavement, pavements in cold and dry weather have a better performance than those in warm and wet weather.
  ◦ In a long-term period, roads present mixed trends in pavement performance reduction for different climate zones. It is reasonable since M&R actions will be implemented on pavement as time goes and our regression models take the prior M&R history as the critical variable. In other words, the observed trends present the combined effects
Figure 8. Validation of the proposed models in the high OS/OW traffic scenarios of case study 1.

Figure 9. Validation of the proposed models in the low OS/OW traffic scenarios of case study 1.
of M&R actions and climatic effects on the pavement later age behaviour.

- The impact of OS/OW loads on roads in the same climate zone:
  - In a short-term period, the pavement performance drops only due to the level of OS/OW loading. The trend clearly shows that: the more OS/OW vehicles, the more damage to the road.
  - In a long-term period, an opposite trend in performance reduction speed can be observed. It is reasonable since the road that transport high volumes of OS/OW vehicles is usually implemented more frequent M&R actions than the one with low OS/OW loading. Again, the observed trends present the combined effects of multiple related factors.

In the future work, the developed pavement performance models have laid a basis for at least three research tasks:

- Developing an optimal routing algorithm to significantly reduce road damage from OS/OW vehicles by considering pavement condition data, which will be integrated into the web GIS OS/OW routing management platform.
- Validating the proposed methodology by considering the impact of M&R activities, since different M&R strategies may induce same difference in pavement PCS before and after the implementation. More future efforts are needed to explain how the M&R work affect the regression models.
- Determining new design criteria and strategies for pavement maintenance under the OS/OW loads. The authors are considering to integrate the proposed method with the Mechanistic-Empirical (ME) pavement design guide.

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Figure 10. Validation of the proposed models in case study 2.


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