Impact of Overweight Traffic on Pavement Life Using Weigh-In-Motion Data and Mechanistic-Empirical Pavement Analysis

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ABSTRACT: The objective of this study is to evaluate 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 WIM data were collected were analyzed to estimate the pavement service life at field condition. The pavement structures considered in the analysis include flexible pavement and composite pavement with different combinations of layer thickness. Different distribution patterns were observed between the overweight and non-overweight traffic in terms of truck classes and axle load spectra. The reduction ratio of pavement life was used to normalize the effect of overweight truck at different conditions. A linear relationship was found between the overweight percentage and the reduction ratio of pavement life regardless of the variation in traffic loading and pavement structure. In general, it shows that 1% increase of overweight truck may cause 1.8% reduction of pavement life. Through the comparison between the pavement life predicted from the M-E analysis and estimated from field performance data, M-E analysis was proved to be a valid approach to quantify the impact of overweight truck on pavement damage in the network level.

INTRODUCTION

During the life of pavement, various types of vehicles will pass on the design lane and numerous factors will influence pavement damage. Traffic loading on road pavements is characterized by a number of different types of vehicles with variations in load magnitude, number of axles, and axle configuration. The increasing axle load and/or total vehicle weight shortens the pavement service life and increases the agency cost to maintain pavement condition at an acceptable level. It is expected that the impact of overweight truck on pavement service life is affected by pavement structure, traffic characteristics, and overweight percentage.

To date, a number of research efforts have been devoted to study the reduction of pavement service life and the increase of life cycle cost associated with overweight trucks. Roberts and Djakfar (2000) studied the impact of increasing the legal gross vehicle weight (GVW) limit as compared to the previous legal GVW. The required overlay thickness for each analysis period and weight scenario was calculated and compared. It was found that the greater increasing of GVW led to more significant decreasing of pavement service life and more overlays. However, the heavier traffic that a road is designed for, the smaller the effect of increasing GVW would result in. Freeman et al. (2000) conducted a study to determine the effect of higher allowable weight limit provisions on pavement maintenance and rehabilitation cost in Virginia. This study included traffic classification, weight surveys, an investigation of subsurface conditions, and comprehensive structural evaluations. The cost of damage to roadway pavements with a higher allowable weight limit was estimated to be $28 million over a 12-year period due to the increased overlay thickness.

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. The factors considered in the analysis include asphalt layer thickness, pavement temperature, subgrade condition, and vehicle speed. Pais et al. (2013) studied the truck factor for the vehicles that travel with axle loads or the total vehicle weight above the maximum legal limits. They also 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.

However, few studies investigated the impact of overweight vehicles on pavement damage considering the detailed traffic characteristics, such as vehicle class and axle configurations. This study aims to accurately quantify the effect of vehicular loading on pavement deterioration using the traffic data measured using the weight-in-motion (WIM). The recent advancement in the mechanistic-empirical pavement design guideline (MEPDG) was adopted in the analysis. This will help state agencies more reliably assess the relative cost shares of damage caused by heavy weight vehicles and allocate resources for pavement maintenance and repair.

OBJECTIVE

The objective of this study is to evaluate 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. The axle load spectra obtained from WIM data were analyzed, respectively, for the non-overweight and overweight traffic. The pavement structures considered in the analysis include flexible pavement and composite pavement with different combinations of layer thickness. The life reduction ratio at different sites due to overweight traffic was calculated. At the same time, field performance data at the sites where the WIM data were collected were analyzed to estimate the pavement service life at field condition.

MECHANISTIC-EMPIRICAL ANALYSIS APPROACH

The mechanistic-empirical pavement design guide (MEPDG) was released in draft form at the conclusion of NCHRP 1-37A project in April, 2004. In 2014, Pavement-ME was released as the next generation of AASHTOWare® pavement design software, which builds upon the MEPDG, and expands and improves the features in the accompanying prototype computational software.

In the MEPDG, structural responses (stresses, strains and deflections) are mechanistically calculated based on material properties, environmental conditions, and loading characteristics. These responses are used as inputs in empirical models to predict pavement performance. The accuracy of empirical models is a function of the quality of the input information and the calibration of empirical distress models to observed field performance. The distresses considered for flexible pavements are: rutting, (bottom-up fatigue cracking, longitudinal (top-down) cracking, thermal cracking, and roughness (ARA 2004).

The MEPDG has a hierarchical approach for the design inputs, defined by the quality of data available and importance of the project, including:

Level 1 - Laboratory measured material properties are required (e.g., dynamic modulus for asphalt concrete, nonlinear resilient modulus for unbound materials). Project-specific traffic data is required (e.g., vehicle class and axle load distributions);

Level 2 - Inputs are obtained through empirical correlations with other parameters (e.g., resilient modulus estimated from CBR values) and state-wide traffic data;

Level 3 - Inputs are selected from a database of national or regional default values according to the material type or highway class (e.g., soil classification to determine the range of resilient modulus, highway class to determine vehicle class distribution).

WIM DATA AND AXLE LOAD SPECTRUM

Traffic data is an important data input for MEPDG and the most accurate method to obtain traffic data is the weight-in-motion (WIM) system. WIM systems can continuously measure and store axle load and axle spacing with supplementary data such as date, time, speed, lane of travel, vehicle type, etc. In this study, WIM data at ten sites located at different routes were obtained from the New Jersey Department of Transportation (NJDOT) and used for level-1 traffic input in the M-E analysis. Axles per truck, monthly adjustment factors, and hourly distribution factors were obtained through the post-processing of WIM data.

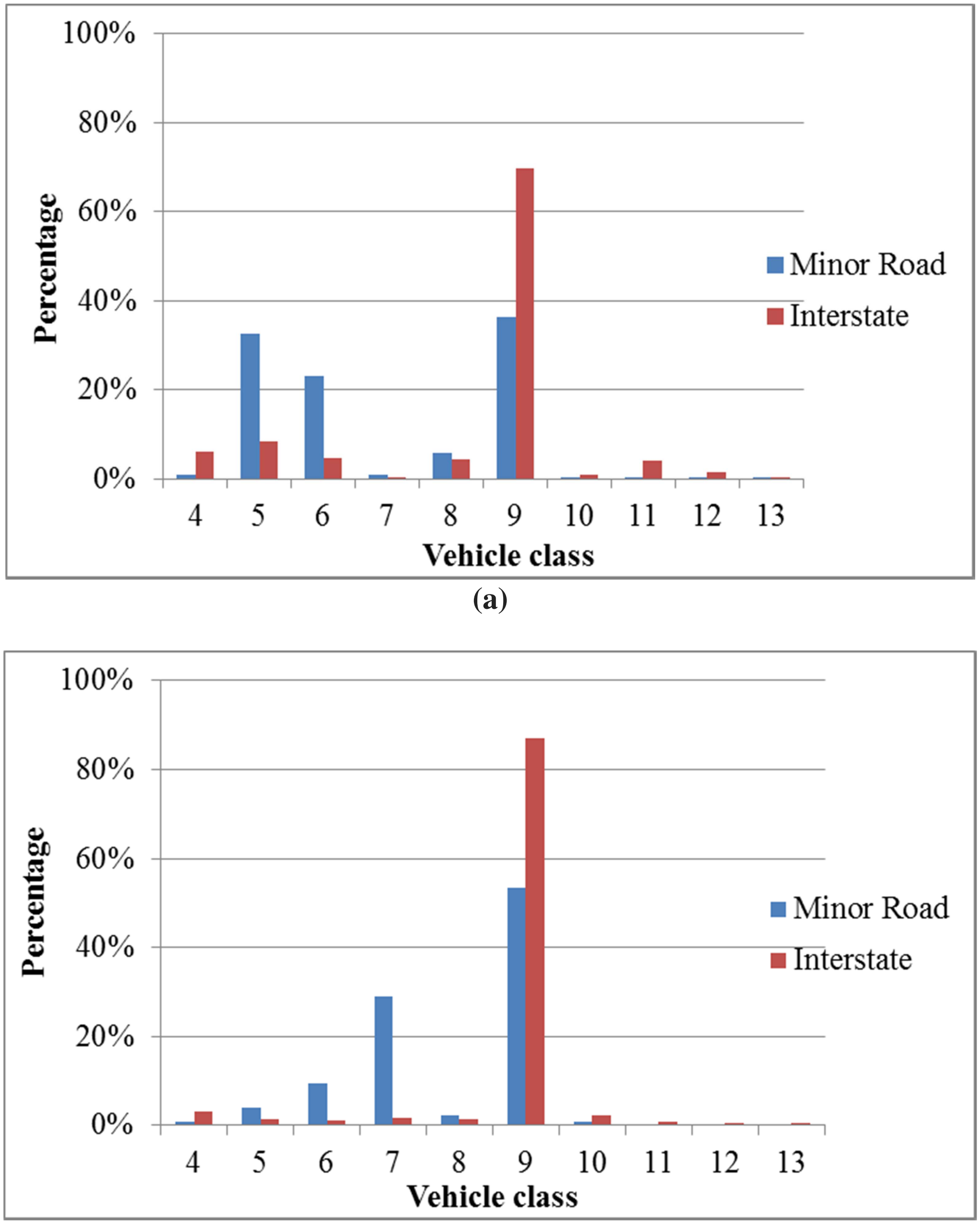
Currently, the New Jersey Department of Transportation legislates 80,000 pound as the legal GVW. The legal axle weight on a single axle is 22,400lbs, and the legal tandem axle weight is 34,000lbs. For a single permit, five dollars per ton is charged once the GVW or axle weight exceeds their legal limits. Besides the excess weight fee, ten-dollar base fee, 12-dollar transaction fee and 5% service fee are included in the permit fee structure. In this study, the WIM data is filtered into two traffic categories. The first category includes the vehicles within the legal weight limit and the second category includes the overloaded vehicles with the GVW or axle load exceeding the legal weight limit.

Table 1 shows the average annual daily truck traffic (AADTT) and the percentage of overweight trucks after analysis of WIM data in 10 selected sites. As expected, the AADTT in the interstate highway is much greater the AADTT in the minor road. However, the percentage of overweight trucks varies in a wide range from 3% to 25%.

Table 1 WIM Data at the Selected Sites

Site	Route type	Average annual daily truck traffic (AADTT)		Percentage of overweight truck
		Total	Overweight	
1	Interstate	11739	1970	17%
2	Interstate	14131	1567	11%
3	Interstate	3572	686	19%
4	Major Highway	8337	558	7%
5	Interstate	10747	275	3%
6	Interstate	13607	899	7%
7	Minor road	928	230	25%
8	Minor road	2710	239	9%
9	Minor road	1348	143	11%
10	Minor road	485	26	5%

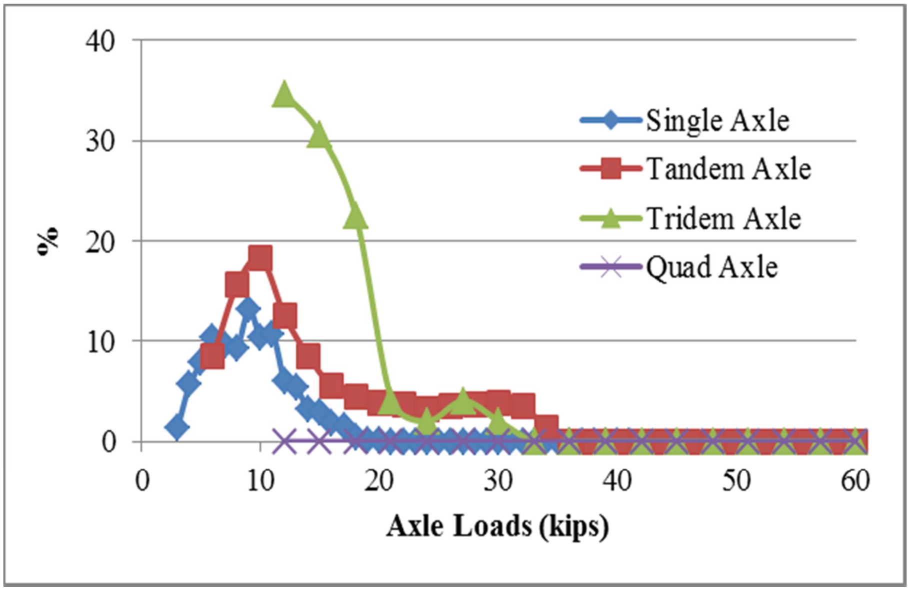
Figures 1(a) an (b) show typical truck class distributions on the Interstate highway and minor road, respectively, for the non-overweight and overweigh traffic. It was found that on the minor road the truck traffic composition for the non-overweight traffic mainly includes class 9 (five-axle, single trailer), class 5 (two-axle, single unit), class 6 (three-axle, single unit); while the truck traffic composition for the overweight traffic mainly includes class 9 (five-axle, single trailer) and class 7 (four or more Axles, Single Unit). On the other hand, on the Interstate highway, class 9 (five-axle, single trailer) is the dominant truck class for both the non-overweight and overweigh traffic.



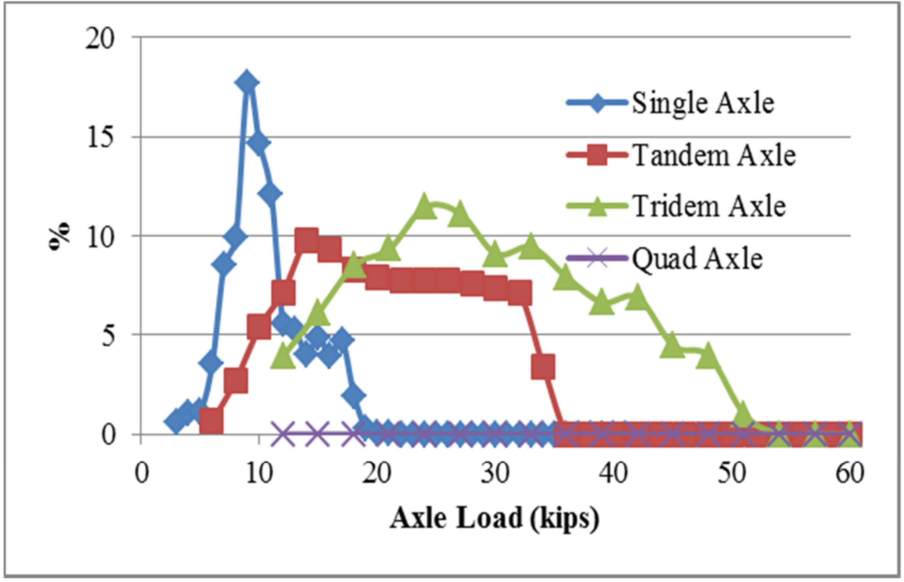
(b)

Figure 1 Vehicle class distributions for (a) non-overweight and (b) overweight traffic

Figure 2 shows the axle load spectra of Class 9 vehicles in the non-overweight traffic, respectively, on the Interstate highway and minor road. The results show that on minor road, the single axle and tandem axle have most axle loads around 10 kips. Most of tridem axles have loads between 10 and 20 kips. On the Interstate highway, the single axle has the similar axle load spectra as the one on minor road. However, the tandem axle has a wide distribution of load ranging from 6 kips to 36 kips and the tridem axle has a wide distribution of load ranging from 12 kips to 51 kips. The data clearly show that the trucks travelled on the Interstate highway have the greater axle loads than the trucks on the minor road.



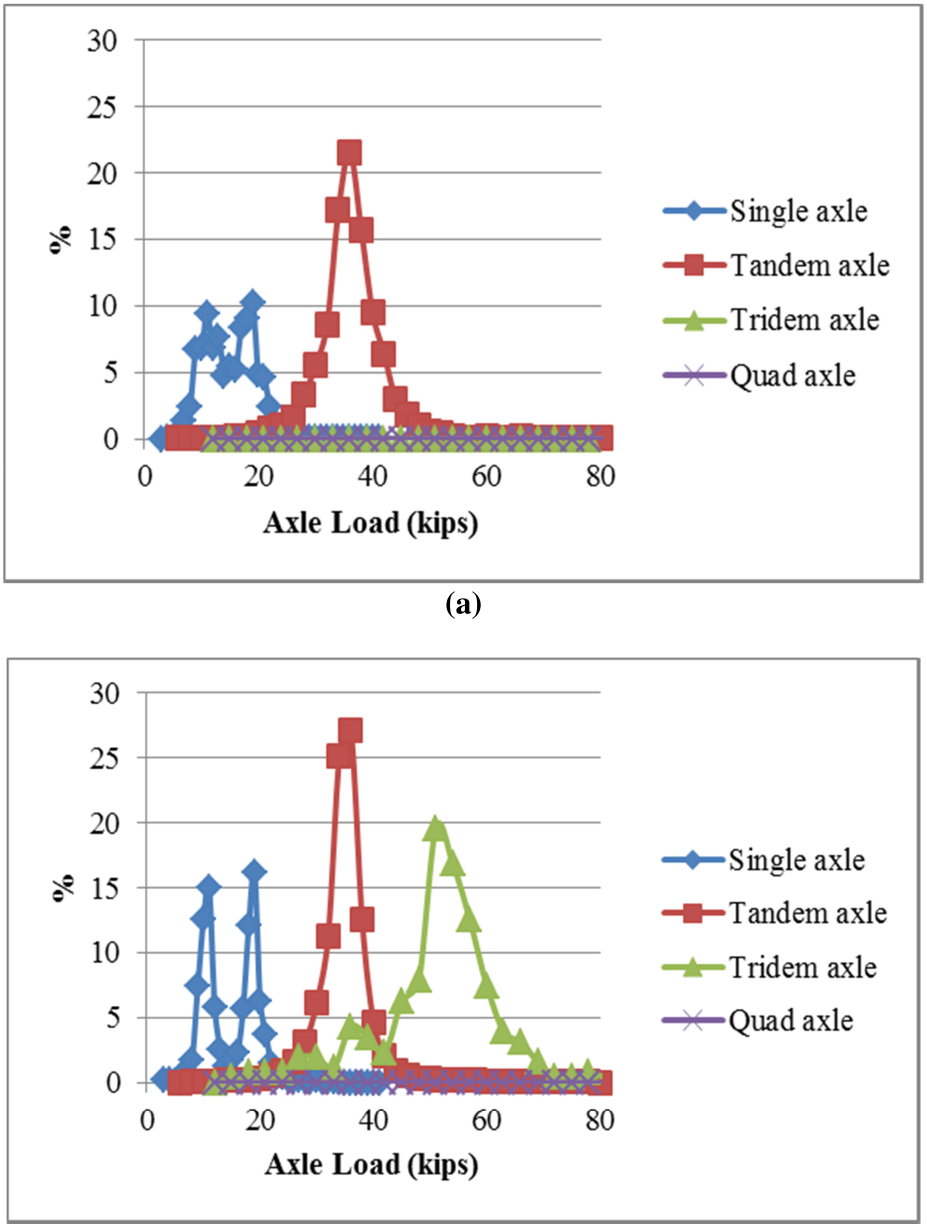
(a)



(b)

Figure 2 Axle load spectra of non-overweight traffic on (a) minor road and (b) Interstate highway (Class 9 vehicle)

Figure 3 shows the axle load spectra of Class 9 vehicles in the overweight traffic, respectively, on Interstate highway and minor road. The results show that the single axle and tandem axle have the similar loading distribution patterns on the Interstate highway and minor road, although the percentage of axle loads within the specific load ranges are different. Two peaks were observed in the distribution of single axle loads and one peak was observed in the distribution of tandem axle loads. On the Interstate highway, the tridem axle has a peak distribution at 50 kips, which contributes significantly to the total vehicle weight.



(a)

(b)

Figure 3 Axle load spectra of overweight traffic on (a) minor road and (b) Interstate highway

M-E PAVEMENT ANALYSIS AT DIFFERENT LOADING SCENARIOS

The pavement life under traffic loading was analyzed using the Pavement-ME software. The pavement structures at the 10 selected sites include both flexible pavement and composite pavement, as shown in Table 2. The level 3 inputs was used for the material properties at each pavement layer, including the dynamic modulus of asphalt concrete, elastic modulus and tensile strength of Portland cement concrete, and resilient modulus of base/subbase layer and subgrade.

Table 2 Summary of Pavement Structures

Site	Pavement type	Layer Thickness (inch)		
		Asphalt	PCC	Base/Subbase
1	Thick Flexible Pavement	11.5	/	20
2		16	/	20
3		12	/	10
4		10.5	/	10
5	Composite Pavement	4.5	10	12
6		3	9	12
7		3.5	7.5	12
8		3.5	7	12
9	Thin Flexible Pavement	4.5	/	20
10		2	/	18

The design reliability is 90% and the default design criteria for various performance indicators were used, as shown in Table 3. The load-related pavement distresses were mainly considered in the analysis including permanent deformation (AC and base rutting) and AC fatigue cracking (top-down and bottom-up). In the Pavement-ME, environmental conditions are simulated by the Enhanced Integrated Climatic Model (EICM) and this study selected Newark, NJ as the climate station.

Table 3 M-E Pavement Design Criteria

Performance criteria	Limit
Initial IRI (in/mile)	63
Terminal IRI (in/mile)	172
AC top-down fatigue cracking (ft/mile)	2000
AC bottom-up fatigue cracking (%)	25
AC thermal fracture (ft/mile)	1000
Permanent deformation - total pavement (in)	0.75
Permanent defamation - AC only (in)	0.25

In order to evaluate the effect of overweight traffic on pavement damage, the reduction ratio of pavement life is calculated using Equation 1.

$$\text{Reduction ratio of pavement life} = \frac{L_0 - Lx}{\mathrm{L}_0} \tag{1}$$

Where, L_0: Pavement life caused by total traffic; and

L_x: Pavement life caused by the non-overweight traffic.

Figure 4 shows the reduction ratio of pavement life as the percentage of overweight truck varies for the 10 selected sites. Linear regression fitting with a relatively high R-square value and statistical test results indicates that a linear relationship may exist regardless of the variation in traffic loading and pavement structure. In general, it shows that 1% increase of overweight truck may cause 1.8% reduction of pavement life. The use of reduction ratio of pavement life is to normalize the effect of overweight truck at different conditions and thus it is more applicable to quantify the impact of overloaded vehicle on pavement damage in the network level. It is expected that the absolute difference of pavement life caused by overweight truck will vary depending on the traffic characteristics, pavement structure and the in-situ condition at a specific pavement segment.

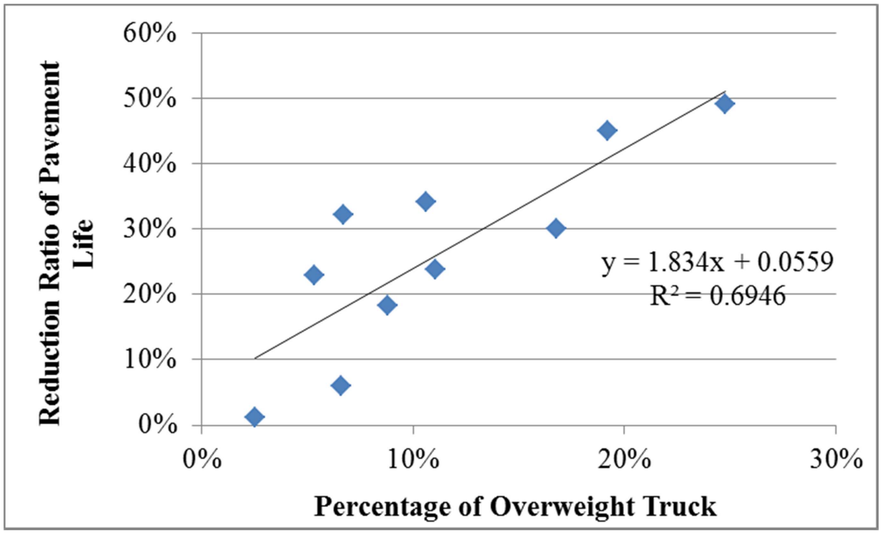


Figure 4 Reduction ratio of pavement life at different percentages of overweight truck

PAVEMENT LIFE ESTIMATED FROM FIELD PERFORMANCE

It is recommended by the AASHTO that local calibration of performance transfer function in the MEDPG should be conducted in order to accurately capture the variation of material and distress development trends. At the time of this study, the local calibration of MEDPG has not been conducted in New Jersey. Therefore, the global parameters that were calibrated based on the long-term pavement performance (LTPP) database were used in the analysis.

In order to verify the M-E analysis results, pavement performance data were extracted from the pavement management database to estimate the pavement service life. The extracted data include Surface Distress Index (SDI) and International Roughness Index (IRI) from 2000 to 2012. It was found that the IRI usually does not reach the failure criteria or the rehabilitation threshold after 10 years. Thus, the SDI is believed to be a better index reflecting pavement deterioration. Essentially, the SDI has a scale of 0-5 and incorporates both the non-load related distresses outside the wheel paths (NDI) and the load related distress index (LDI). The NJDOT defines the pavement condition as poor when SDI < 2.4 or IRI > 170in/mile and as good when SDI > 3.5 and IRI < 95in/mile.

Therefore, the service life in the study is determined as the time period before the SDI drops to 2.4.

Various model forms (such as linear, exponential, logarithmic, power, and polynomial models) can be used to estimate the best fit to pavement condition data based on maximizing the goodness of fit, R-square, A majority of model forms do not constrain the curve to fit within the boundaries and may not simulate the development trend for SDI in a correct way. For instance, it can be observed from Figure 5 that during the first couple of years, the SDI declines slowly. Afterward, it may start to drop rapidly and finally decrease gradually as a step function. Under this scenario, the linear model and exponential model can hardly predict the trend. Sigmoidal (S-shape) model has been shown to provide high accuracy as well as constraining the curve to fit within pavement condition boundaries (Hajek et al. 1985; Jackson et al. 1996). Typical form of sigmoidal model is shown in Equation 2. It ensures that the performance curve is constrained within the condition model boundaries between SDI=0 and 5. After the model parameters are determined, the pavement life before the SDI reaching 2.4 was calculated for different sites. It is noted that the maximum life of 20 years is used in the estimation of field condition.

$$SDI = SDI_0 - \exp(a - b * c^{(\ln(\frac{1}{Age}))}) \qquad (2)$$

Where,
SDI = Surface distress index;
SDI_0 = Surface distress index at year zero (usually 5);
Age = the year since the initial construction of the last rehabilitation treatment; and
a,b,c = model coefficients with a = $\ln(SDI_0)$ and $SDI_{terminal}$=0.

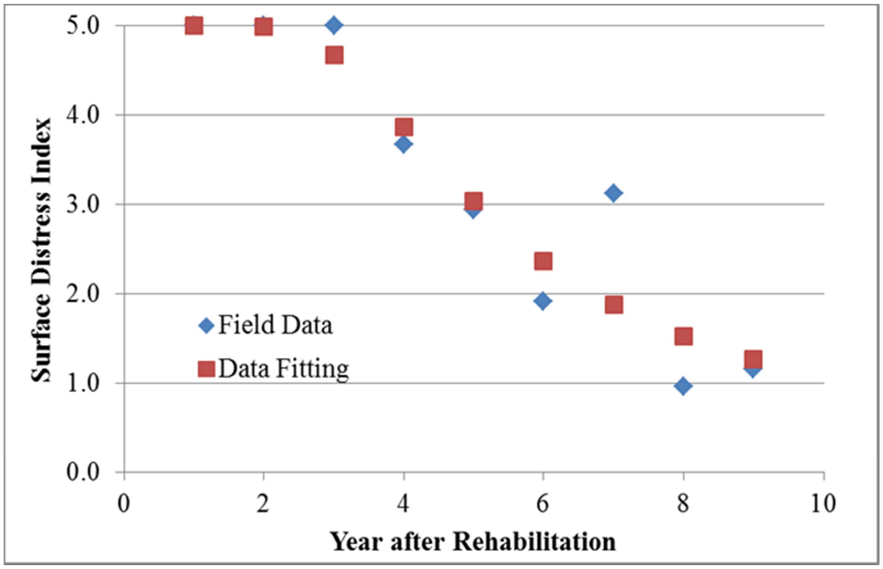


Figure 5 Deterioration trends of field performance data

Figure 6 compares the pavement life calculated from the M-E analysis and the pavement life estimated from the field data. The high R-square value of linear regression indicates that the M-E analysis results were consistent with the pavement performance deterioration trend observed in the field. This proves that the M-E analysis results could be used to quantify the impact of overweight truck on pavement damage in the network level. It is noted that the differences between the M-E analysis results and the field performance is intrinsic because different failure criteria were considered. On the other hand, local calibration and level 1 input become more critical for if the M-E analysis is used for pavement design purpose.

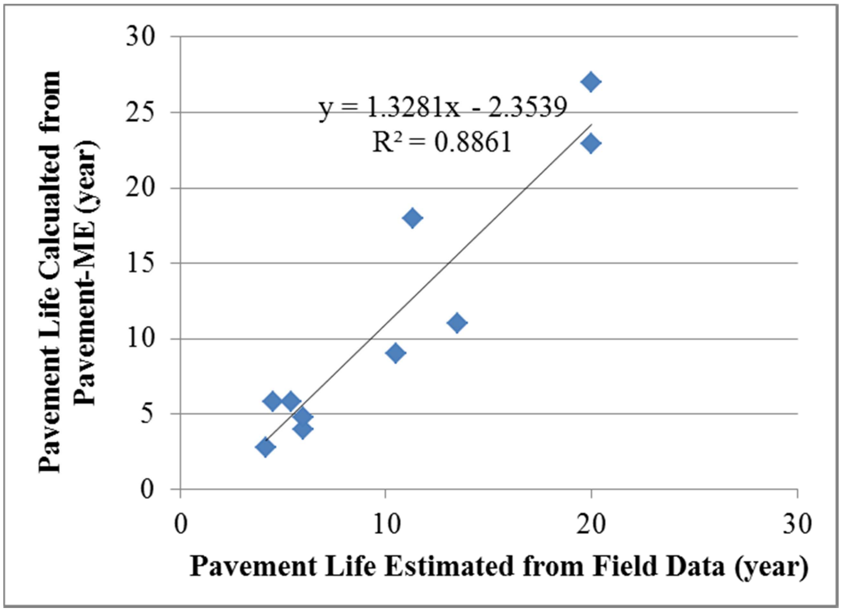


Figure 6 Comparison of pavement life from M-E analysis and field performance data

CONCLUSIONS

The impact of overweight vehicles on pavement life was analyzed using WIM data and mechanistic-empirical pavement analysis. Different distribution patterns were observed between the overweight and non-weight traffic in terms of truck classes and axle load spectra. The reduction ratio of pavement life was used to normalize the effect of overweight truck at different conditions. A linear relationship was found between the overweight percentage and the reduction ratio of pavement life regardless of the variation in traffic loading and pavement structure. In general, it shows that 1% increase of overweight truck may cause 1.8% reduction of pavement life. Through the comparison between the pavement life predicted from the M-E analysis and estimated from field performance data, M-E analysis was proved to be a valid approach to quantify the impact of overweight truck on pavement damage in the network level. Future work will be conducted to validate this approach using more pavement sections and analyze the impact of overweight trucks on pavement life cycle cost.

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