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# Characterizing Horizontal Response Pulse at the Bottom of Asphalt Layer Based on Viscoelastic Analysis

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**Abstract:** Fatigue life of asphalt mixes in laboratory tests is usually determined by applying a haversine load with a specific frequency (usually 10Hz). However, the pavement structure, loading and environmental conditions affect the shape and duration of horizontal stress and strain pulse at the bottom of asphalt layer. In this study, the effect of most important factors on the duration of longitudinal and transverse response pulses has been explored and some equations with good accuracy were proposed for determining the duration of tensile stress and strain pulse at the bottom of asphalt layer in both longitudinal and transverse direction. To this end, total of 112 analyses were conducted using 3D-Move dynamic analysis program and in each case, longitudinal and transverse response pulses were determined. With respect to this fact that the haversine function usually used in laboratory fatigue tests, this wave shape was fitted to the computed response pulses and duration of stress and strain pulse were determined. Proposed equations can be used for determining the frequency of loading in HMA fatigue tests under both controlled stress and controlled strain modes.

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***Key words**: Asphalt layers; Fatigue; Pulse duration; Tensile responses.*

## Introduction

Fatigue cracking, due to repeated traffic load, is the most common mode of failure for asphalt pavements. Loading, environmental conditions and pavement structure are the most effective factors that influence the shape and duration of response pulse at the bottom of asphalt layer as well as fatigue cracking of asphalt layer. In addition, fatigue life of asphalt mixes in laboratory tests usually is determined by applying a haversine load with a specific frequency (duration). However, the frequency (time duration) and shape of horizontal stress pulse and strain pulse in both longitudinal and transverse directions depend on the structural properties of pavement layers.

Several research works were conducted to determine the duration of vertical stress pulse at different depth of asphalt layers, and some relations were proposed to this end [1-4]. In spite of all the efforts made to determine the duration of vertical stress pulse at different depths of the asphalt layer, little effort has been made to determine the shape and duration of stress pulse in horizontal directions at the bottom of the asphalt layer.

Brown [5] derived an equation to calculate the loading time as a function of both vehicle speed and depth beneath the pavement surface. The loading time was considered as the average of the pulse times of the stresses in the three directions as obtained from the elastic layered theory. The relationship between the loading time t (s), depth d (m), and vehicle speed v (km/h) is as follows:

$$log(t) = 0.5d + 0.2 - 0.94log(V) \quad (1)$$

When Eq. (1) is plotted for different speeds and thicknesses between 150 and 400 mm, it can be seen that the approximation t = 1/V seconds (V = average speed in km/h) is a reasonable fit for this range of thicknesses [6].

In the development of the Mathematical Model of Pavement Performance (MMOPP), Ullidtz [7] used the loading time corresponding to the middle of the asphalt layer. It was calculated on the simplified assumption that the load at that depth is uniformly distributed over a circular area with the radius $a+ h_i/2$, where a is the radius of the contact area and $h_1$ is the thickness of the asphalt layer. Thus, he defined the time of loading as:

$$t_w = \frac{(2a + h_1)}{V} \quad (2)$$

where $t_w$ is time of loading, $a$ is the radius of the contact area, $h_i$ is the thickness of the asphalt layer and $V$ is the vehicle speed. He mentioned that in this way of calculating the loading time, no reductions are made for the influence of dual tires or for lateral distribution of the loads, adding that the results should, therefore, be on the conservative side [7].

Garcia and Thompson [8] measured the longitudinal and transverse tensile strain pulses in four sections tested with the accelerated pavement testing machine (ATLAS). The range of speeds was between 3.22 to 16.09 km/h. A very strong relationship between the longitudinal and transverse pulse durations was found. In general, the transverse pulse durations were about three times those in the longitudinal direction. They concluded that the haversine function was the best representation for the longitudinal and the transverse strain pulses. They also founded that the Ullidtz method is a very accurate method to estimate the measured strain pulse times in HMA layer.

Robbins [9] used the instrumented sections of the National Center of Asphalt Technology (NCAT) to validate the procedure proposed by the MEPDG to calculate the pulse duration. She developed a

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regression model for the duration of longitudinal strain pulse at the bottom of asphalt layer with three variables:

$$t = j\,ln(h) + V^{k} + T^{l} + m \tag{3}$$

in which $t$ is strain pulse duration and $h$ is thickness of asphalt layer; $V$ is vehicle speed and $T$ is mid-depth temperature; also $j$, $k$, $l$ and $m$ are regression coefficients.

Hernandez [10] performed an experimental testing program at the Accelerated Pavement Load Facility (APLF) of Ohio University on four pavement test sections. The result indicates that the applied load has a small influence on the longitudinal load duration time of the HMA layer bottom strain. On the other hand, the transverse one is affected by the magnitude of the applied load. In addition, the lowest temperature had the highest longitudinal load duration in all the cases, and it decreases as the temperature is increased. It was noted that the influence of temperature is not very significant. Restrepo-Velez [11] analyzed the performance of perpetual pavements in use by the Ohio Department of Transportation. The pavement responses, collected from the Controlled Vehicle Loading Test, conducted on the perpetual section AC 664, of the WAY-30 project, were the basis of the study. The effects of several factors on the tensile strains and the loading pulse durations of the pavement, including speed, temperature, applied load, and lateral wheel offset, were evaluated. she also concluded that greater pulse durations occurred at the lowest values of speed and temperature. Additionally, she compared the observed responses with pavement responses predicted using the Mechanistic-Empirical Pavement Design Guide (MEPDG) and the multi-layer elastic analysis software, JULEA and found that the MEPDG procedure led to an over-prediction of the strain pulse durations of around 80% compared to those measured in the field. Recent studies show that some factors such as modulus of subbase and subgrade layers and thickness of granular layers have a slight effect on the shape and duration of tensile pulses at the bottom of asphalt layer [12].

The objective of this paper is to characterize the most important factors that influence the shape and duration of response pulses at the bottom of asphalt layer and to propose some regression models for predicting the response pulse duration (frequency) based on fitted haversine function to response pulses resulted from viscoelastic analysis. By applying these equations the frequency of loading in HMA fatigue laboratory tests such as 4PBB and IDT fatigue tests can be determined more realistically based on three parameters including moving wheel speed, HMA temperature and HMA thickness.

## Analysis of Pavement Sections Using 3D-Move

In this research, the viscoelastic analysis of pavement sections was completed by 3D-Move program. The finite-layer approach three-dimensional moving load analysis (3D-Move) has been developed at the University of Nevada, Reno (UNR) by siddhartan et al. [13] and treats each pavement layer as a continuum and uses the Fourier transform technique. The finite-layer method is much more computationally efficient than the moving load models based on the finite element method [14]. In addition, rate-dependent material properties (viscoelastic) can be accommodated by the approach. A study by Siddharthan et al. [15] reported on the validation of their approach using: (1) results from existing analytical solutions and (2) laboratory responses measured in two foam-rubber models. In addition, a field verification program undertaken to validate the approach using pavement response data from two well documented full-scale field tests (Penn State Univ. test track and Minnesota road tests) have also been reported [16].

Two four-layered pavement sections including one thin section and one thick section were considered. HMA layer was treated as linear viscoelastic and other layers were assumed to be linear elastic. Layer properties for these sections are given in Table 1.

Witczak predictive equation was used to generate the dynamic modulus master curve of HMA layer [3]. Witczak predictive equation is as follows:

$$\begin{aligned}\log E^* &= 3.750063 + 0.2932\rho_{200} - 0.001767(\rho_{200})^2 \\ &- 0.058097V_a - 0.802208\left(\frac{Vb_{eff}}{Vb_{eff} + V_a}\right) \\ &+ \frac{3.871977 - 0.0021\rho_4 + 0.003958\rho_{3/8}}{1 + e^{-0.603313 - 0.313351\log(f) - 0.393532\log(\eta)}} \\ &- \frac{0.000017(\rho_{3/8})^2 + 0.005470\rho_{3/4}}{1 + e^{-0.603313 - 0.313351\log(f) - 0.393532\log(\eta)}}\end{aligned} \tag{4}$$

where,
$E^*$ = dynamic modulus, psi,
$\rho_{200}$ = % passing the #200 sieve,
$\rho_4$ = cumulative % retained on the #4 sieve,
$\rho_{3/4}$ = cumulative % retained on the #3/4 sieve,
$\rho_{3/8}$ = cumulative % retained on the #3/8 sieve,
$f$ = frequency in Hz,
$Vb_{eff}$ = effective bitumen content, % by volume,
$V_a$ = air void content, and
$\eta$ = bitumen viscosity, $10^6$ Poise.
The bitumen viscosity varies with temperature according to Eq. (5):

$$\log(\log(\eta)) = \mathrm{A} + \mathrm{VTS}\log(\mathrm{T_R}) \tag{5}$$

where,
$\eta$ = binder viscosity expressed in cP,

**Table 1.** Pavement Sections Considered in This Study.

| Layer | Thickness [cm] | | Stiffness | Poisson's Ratio | Unit Weight | Damping |
|---|---|---|---|---|---|---|
| | Thick | Thin | [MPa] | | [kg/m$^3$] | [%] |
| HMA | 35 | 10 | E* by Witczak Eq. | 0.35 | 2320 | 10 |
| Granular Base | 30 | 10 | 207 | 0.35 | 2160 | 5 |
| Granular Subbase | 40 | 15 | 138 | 0.40 | 2070 | 5 |
| Subgrade Soil | - | - | 50 | 0.45 | 1990 | 5 |

**Table 2.** Assumed Inputs for Generating Dynamic Modulus Based on Witczak Predictive Equation.

| HMA Properties | $\rho_4$[%] | $\rho_{3/4}$[%] | $\rho_{3/8}$[%] | $\rho_{200}$[%] | $Vb_{eff}$[%] | $V_a$[%] | A | VTS |
|---|---|---|---|---|---|---|---|---|
| Value | 1 | 10 | 30 | 6 | 10 | 4 | 10.6508 | -3.5537 |

$T_R$ = temperature in degree Rankine, and
A and VTS = regression parameters.

Volumetric specifications of HMA and regression parameters of assumed binder are presented in Table 2.

Each pavement section was analyzed under a moving single wheel load having uniform contact pressure of 690 kPa and contact radius of 12 cm. Sections were analyzed according to three HMA temperatures (5, 25 and 50$^o$C) and twelve rolling wheel speeds (10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110 and 120 km/h). Also in each case, 20 additional analyses were conducted by altering the thickness of HMA, thickness of base and thickness of subbase.

By this way, total of 112 analyses were conducted in case of both thin and thick sections by means of 3D-Move program. After each analysis the longitudinal stress pulse, transverse stress pulse, longitudinal strain pulse and transverse strain pulse at the bottom of asphalt layer were recorded in a database.

## Fitting Haversine Function to Response Pulses

The longitudinal and transverse stress and strain pulses that were induced at the bottom of HMA layer resembled the pulse in Fig. 1, such that at high and moderate temperatures, the response pulse in longitudinal direction generally consists of two compression zones and one tension zone, while at the low temperatures it only consists of tension zone. In case of transverse strain pulse, only at high temperature there are three distinct zones and at low and moderate temperatures the HMA layer only experiences tension strain. The strain pulses computed by 3D-Move were very similar to those observed in full-scale pavement tests [8, 9]. In this research only the tension zone of longitudinal and transverse pulses was considered for fitting haversine function.

For each record of database, the haversine function was fitted to analytical response pulse using weighted nonlinear regression method. The weighted method makes it possible a better fitting of haversine function to higher values of normalized pulse. Haversine function can be expressed as follows:

$$y(x) = sin^2(\frac{\pi}{2} + \pi\frac{x}{d}) \tag{6}$$

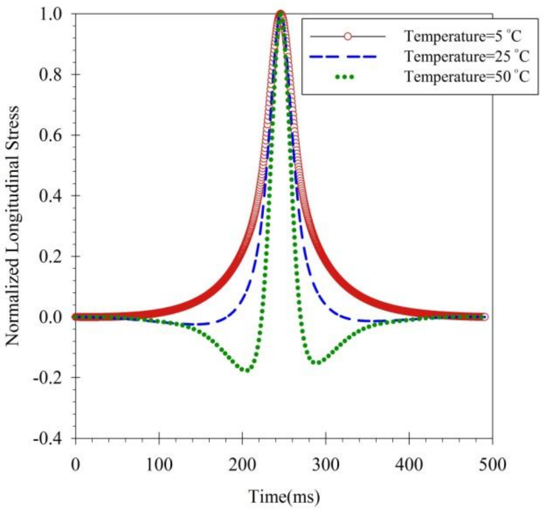
in which, d is duration of pulse and y(x) is normalized amplitude of pulse with respect to time x. Before fitting haversine function to response pulse, the response pulse was normalized by dividing all data points to the maximum value. The frequency histogram of coefficients of determination ($R^2$) resulted from nonlinear regression is given in Fig. 2.

As can be seen, in case of all responses the maximum and minimum value of $R^2$ is 0.99 and 0.83, respectively. Also it can be concluded that haversine function is fitted to stress and train pulse in longitudinal direction better than transverse direction. This finding is in agreement with observation of Garcia and Tompson [8].

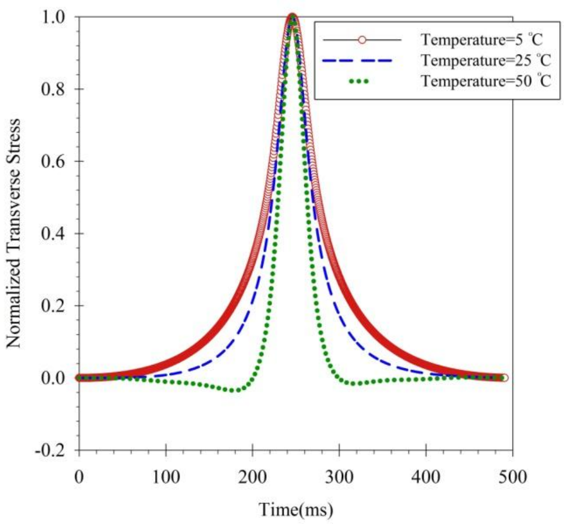
After fitting haversine function to analytical response pulses, the duration of pulse in milli seconds was computed for further analyses.

## Predicting the Duration of Response Pulses

For developing an equation for predicting the duration of response pulse, it is beneficial to study the relation of response duration and effective parameters. For developing an equation for each section, two effective parameters including moving wheel speed and temperature should be studied. Relation of response duration and HMA temperature at speed of 50 km/h is illustrated in Fig. 3. As can be seen, duration can be written as a linear function of Temperature, although in case of transverse strain pulse, quadratic function is more appropriate but still linear function is adequate.




(a)




(b)

**Fig. 1.** Normalized Horizontal Stress vs. Time at Different Temperature (a) Longitudinal Stress (b) Transverse Stress.

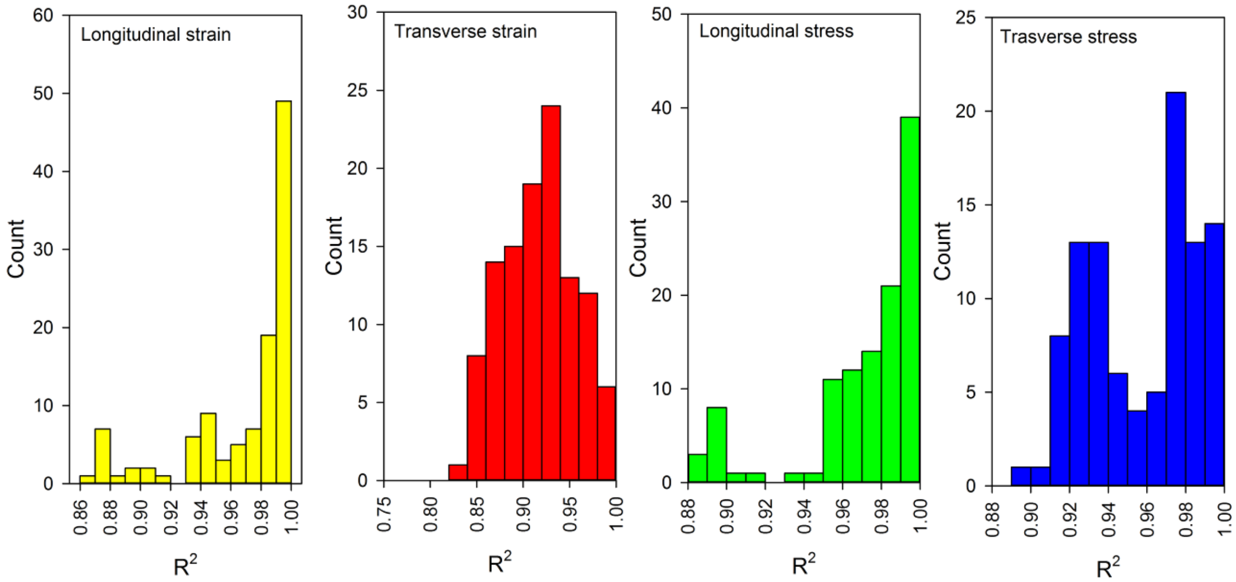



**Fig. 2.** Frequency Histogram of Coefficient of Determination ($R^2$) Resulted from Fitting Haversine Function.

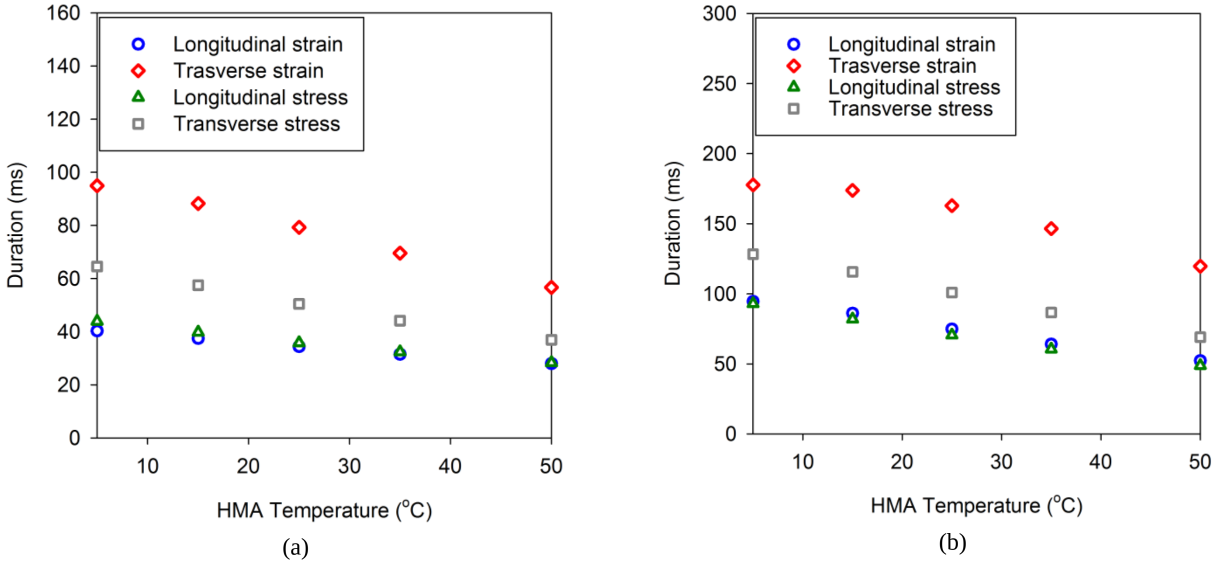



**Fig. 3.** Relation between Duration and HMA Temperature: (a) Thin Section (b) Thick Section.

Relation of response duration and moving wheel speed at HMA temperature of 25°C is illustrated in Fig. 4. It can be seen that there is a linear relation between duration and reciprocal of speed. This finding confirms previous research works done by Brown [6].

Trend of duration variations with respect to moving speed and HMA temperature were explored at other temperature and moving speed and it was approved that this relations are valid in other cases.

For predicting the duration of stress and strain pulses at both longitudinal and transverse directions, following equation is proposed:

$$D = \frac{1}{S}(a + bT). \tag{7}$$

where:

$D$ = duration of response pulse (ms)

$S$ = moving speed (km/h)

$T$ = HMA temperature (°C)

$a$ and $b$ = regression coefficients.

This equation is applicable for a specific pavement section and can be used to predict response duration at different speeds and HMA temperatures. Results of fitting Eq. (7) to durations computed from regressed haversine pulse are given in Table 3. As it is shown, duration of all response pulses including longitudinal strain, transverse strain, longitudinal stress and transverse stress can be predicted accurately by applying Eq. (7).

The thickness of HMA layer is one of the most important factors that affect the shape and duration of response pulses at the bottom of asphalt layer. For developing an equation which can be applicable in case of other pavements with different HMA thickness, following equation is proposed:

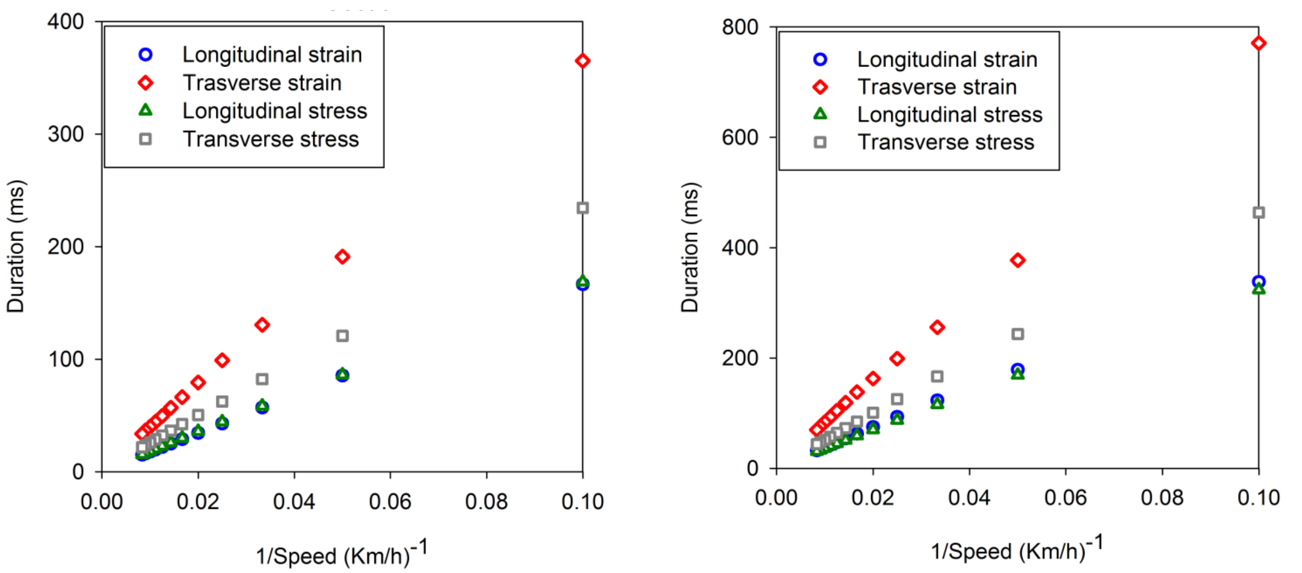



**Fig. 4.** Relation between Duration and Moving speed: (a) Thin Section (b) Thick Section.

**Table 3.** Result of Regression Analysis for Prediction of Response Duration Based on Eq. (7).

| Pavement Section Type | Response Type | Regression Coefficients a | Regression Coefficients b | $R^2$ |
|---|---|---|---|---|
| Thick Section | Long. Strain | 4778.65 | -46.35 | 0.994 |
| | Trans. Strain | 9662.02 | -78.42 | 0.989 |
| | Long. Stress | 4711.56 | -49.97 | 0.993 |
| | Trans. Stress | 6598.70 | -68.04 | 0.993 |
| Thin Section | Long. Strain | 2025.53 | -13.83 | 0.996 |
| | Trans. Strain | 4757.69 | -43.11 | 0.994 |
| | Long. Stress | 2175.95 | -17.77 | 0.994 |
| | Trans. Stress | 3189.08 | -30.88 | 0.992 |

**Table 4.** Result of Regression Analysis for Prediction of Response Duration Based on Eq. 8.

| Pavement Section Type | Response Type | Regression Coefficients a | Regression Coefficients b | Regression Coefficients c | $R^2$ |
|---|---|---|---|---|---|
| Thin & Thick Sections | Long. Strain | 1694.59 | -29.89 | 75.26 | 0.981 |
| | Trans. Strain | 3642.69 | -60.35 | 157.26 | 0.991 |
| | Long. Stress | 1925.35 | -33.66 | 66.85 | 0.979 |
| | Trans. Stress | 2708.14 | -49.18 | 96.24 | 0.985 |

$$D = \frac{1}{S}(a + bT + cH) \quad (8)$$

where:

$D$ = duration of response pulse (ms)

$S$ = moving speed (km/h)

$T$ = HMA temperature ($^o$C)

$H$ = HMA thickness (cm)

$a$,$b$, and $c$ = regression coefficients.

Eq. (8) was fitted to all records of database (112 data points). The regression coefficients as well as coefficient of determination are given in Table 4.

Goodness of fit of Eq. (8) to analytical duration is illustrated in Fig. 5. It can be seen that the Eq. (8) is quite appropriate for predicting horizontal stress and strain duration in both longitudinal and transverse directions. One interesting finding is that tensile strain pulse duration in transverse direction is almost twice of that in longitudinal direction.

## Conclusion

The following conclusions can be drawn from the present study:

1. The strain pulses computed by 3D-Move were very similar to those observed in full-scale pavement tests.
2. Haversine function was fitted to longitudinal response pulses better in comparison with transverse response pulses.
3. By fitting haversine function using weighted nonlinear regression, the duration of tensile strain pulse in longitudinal direction is almost twice of that in transverse direction.
4. Four equations were proposed successfully for determining the duration of tensile response pulses at the bottom of asphalt layer in case of thick and thin pavement sections.
5. Four equations were proposed for determining the duration of stress and strain tensile pulses at the bottom of HMA layers which are applicable for conventional flexible pavements with different HMA thicknesses.
6. Proposed equations allow determining the frequency of loading in HMA fatigue laboratory tests such as 4PBB and IDT fatigue tests more realistically based on three parameters including moving wheel speed, HMA temperature and HMA thickness.

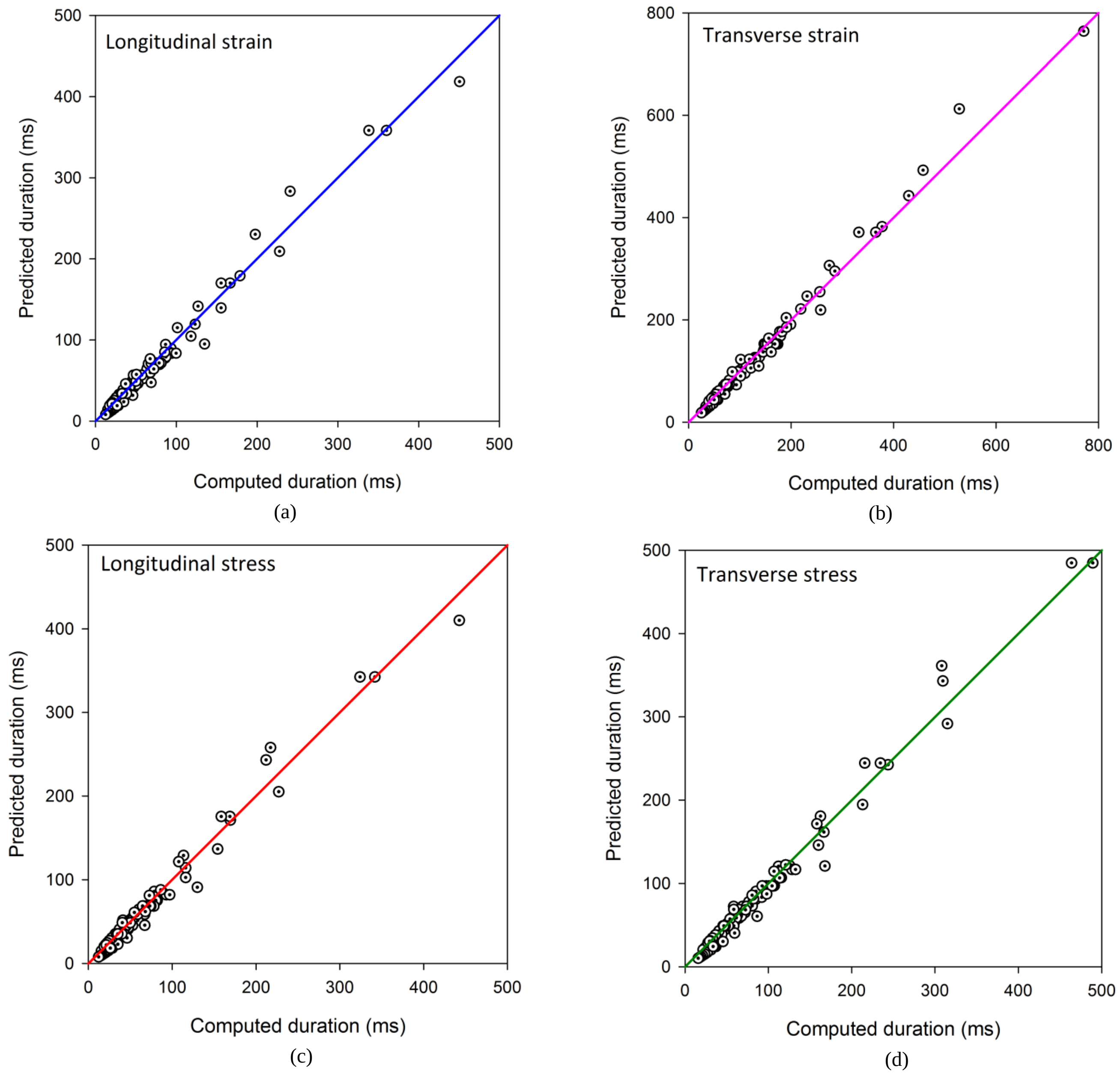



**Fig. 5.** Goodness of Fitting of Eq. (8).

## References


1. McLean, D.B. (1974). Permanent deformation characteristics of asphalt concrete, University of California, Institute of Transportation and Traffic Engineering, Berkeley, CA, USA.
2. Barksdale, R.D. (1971). Compressive stress pulse times in flexible pavements for use in dynamic testing, *Highway Research Record*, No. 345, pp. 32-44.
3. NCHRP (2004). Guide for Mechanistic–Empirical Design of New and Rehabilitated Pavement Structures, Final Report for Project 1-37A, National Cooperative Research program.
4. Hu, X., Zhou, F., Hu, S., and Walubita, L.F. (2010). Proposed Loading Waveforms and Loading Time Equations for Mechanistic-Empirical Pavement Design and Analysis, *Journal of Transportation Engineering*, 136, pp. 518-527.
5. Brown, S. (1973). Determination of Young's modulus for bituminous materials in pavement design, *Highway Research Record*, No. 431, pp. 38-49.
6. Brown, S.F. (2005). Note on the Loading Time Effect on Asphalt Stiffness, NCHRP 1- 40A(O1), Committee Notes.
7. Ullidtz, P. (2005). Frequency / Loading Time, NCHRP 1-40A(O1), Committee Notes.
8. Garcia, G. and Thompson, M.R. (2008). Strain and pulse duration considerations for extended-life hot-mix asphalt pavement design, *Transportation Research Record*, No. 2087, pp. 3-11.
9. Robbins, M.M. (2009), An investigation into dynamic modulus of hot-mix asphalt and Its contributing factors, M.S. Thesis, Auburn University, Auburn, Alabama, USA.
10. Hernandez, J.A. (2010). Evaluation of the response of perpetual

pavement at accelerated pavement loading facility: Finite element analysis and experimental investigation, M.S. Thesis, Ohio University, Ohio, USA.
11. Restrepo-Velez, A.M. (2011). Long-Term Performance of Asphalt Concrete Perpetual pavement WAY-30 Project, M.S. Thesis, Ohio University, Ohio, USA.
12. Fakhri, M., Ghanizadeh, A.R., and Dolatalizadeh, M. (2013). Effect of different parameters on the shape and duration of horizontal stress and strain pulse at the bottom of asphalt, *2nd Middle East Symposium of Asphalt Thechnology (MESAT)*, American University of Sharjah, United Arab Emirates.
13. Siddharthan, R., Krishnamenon, N., and Sebaaly, P. (2000). Pavement response evaluation using finite-layer approach, *Transportation Research Record*, No. 1709, pp. 43-49.
14. Huhtala, M., and Pihlajamaki, J. (1992). New concepts on load equivalency measurements, *7th International Conference on Asphalt Pavements*, Nottingham, UK, 1992.
15. Siddharthan, R.V., Krishnamenon, N., and Sebaaly, P.E. (2000). Finite-layer approach to pavement response evaluation, *Transportation Research Record*, No.1709, pp. 43-49.
16. Siddharthan, R.V. Krishnamenon, N., El-Mously, M., and Sebaaly, P.E. (2002). Validation of a pavement response model using full-scale field tests, *International Journal of Pavement Engineering*, 3, pp. 85-93.