ASSESSMENT OF PAVEMENT DEFLECTION-CAUSED FUEL CONSUMPTION VIA FWD DATA

Abbas Booshehrian, Ph.D. Candidate – Corresponding Author
Department of Civil, Environmental, and Geo- Engineering
University of Minnesota
179 Civil Engineering Building, 500 Pillsbury Drive S.E.,
Minneapolis, MN 55455-0116
Phone: (508) 971-3735
Fax: (612) 626-7750
Email: boosh002@umn.edu

Arghavan Louhghalam, Ph.D.
Department of Civil & Environmental Engineering
Massachusetts Institute of Technology
77 Massachusetts Ave, Room 1-382,
Cambridge, MA 02139
Email: arghavan@mit.edu

Lev Khazanovich, Ph.D.
Department of Civil, Environmental, and Geo- Engineering
University of Minnesota
160 Civil Engineering Building, 500 Pillsbury Drive S.E.,
Minneapolis, MN 55455-0116
Phone: (612) 624-4764
Fax: (612) 626-7750
Email: khaza001@umn.edu

Franz-Josef Ulm, Ph.D.
Department of Civil & Environmental Engineering
Massachusetts Institute of Technology
Bldg. 1-263, 77 Massachusetts Avenue
Cambridge, MA 02139
Phone: 617-253.3544
Email: ulm@mit.edu

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ABSTRACT
The recently developed deflection-induced pavement-vehicle interaction analysis links the structural performance of the pavement to the fuel consumption of moving vehicles and the subsequent greenhouse gas emissions during the pavement use-phase. Accurate estimations of these impacts are tightly dependent on the proper evaluation of pavement structural parameters, including the properties of the surface course and underlying layers. A recent study demonstrated that inertia and damping effects of underlying layers must be taken into account for pavements subjected to dynamic loads, and that accurate parameters of pavement model could be backcalculated using the falling weight deflectometer measurements. In this paper, the pavement-vehicle interaction analysis is modified accordingly. Then, a case study is performed using multiple time histories of falling weight deflectometer deflections collected over a year's time for a rigid and a flexible pavement. Analysis of deflection basins showcases how falling weight deflectometer measurements can be used for estimating the deflection-induced vehicle fuel consumption for both rigid and flexible pavements. The simplicity and accuracy of the demonstrated analyses show a lot of promise for wider application of this methodology, especially regarding sustainable development of pavement network.

BACKGROUND

It is well established that road properties affect rolling resistance, and thus, fuel consumption and corresponding environmental footprint (*1-4*). Alongside pavement roughness and texture (*5-8*), dissipation of energy due to pavement deformation is an important contributor to rolling resistance (*9*). The deflection-induced dissipated energy contributes to excess fuel consumption and use-phase greenhouse gas emission. In order to develop sustainable transportation systems, it is necessary to develop quantitative tools that establish the link between pavement deformation and life-cycle energy consumption, which has been the topic of few recent studies (*6,9-11*). Some quantitative tools have been proposed. For instance, deflections recorded by Benkelman beam rebound were used by Zaabar and Chatti as an indicating factor in estimating the fuel consumption (*6*). Another approach was the deflection-induced pavement-vehicle interaction (PVI) model proposed by Louhghalam et al. PVI quantifies the dissipated energy due to viscous deformation of pavement under a moving load and evaluates the related fuel consumption and environmental footprint as functions of structural and material properties of pavement (*12,13*).

In order to determine the surface deformation and the resulting dissipated energy, the PVI model proposed by Louhghalam et al. (*12*) idealizes both rigid and flexible pavements as a viscoelastic plate resting on a weightless elastic Winkler foundation. This model is computationally efficient, and so it is an attractive tool for an analysis that up-scales the pavement-scale emission to network level environmental impact (*14,15*). However, the simplicity of this model does not guarantee its ability to properly describe the pavement behavior. Especially for the case of a flexible pavement, the use of a Winkler foundation model is not a common practice. Therefore, the accuracy of this idealization must be tested when pavement is subjected to dynamic loads. Also, regardless of the accuracy of the selected model, pavement structural parameters are needed to perform the PVI analysis.

The dynamic nature of the falling weight deflectometer (FWD) loading mechanism and its similarity with moving loads make the FWD time history deflection data a viable source for 1) evaluation of the ability of the selected model in describing the pavement behavior, and 2) development of a rational approach for the assignment of model parameters for PVI analysis. Since FWDs are commonly used by roadway agencies, the FWD deflection data could be used for rational analysis of vehicles fuel consumption on roadways in network planning and pavement management decision-making.

A numerical-based dynamic backcalculation method was recently developed to analyze the FWD deflection time histories and indicate the pavement model parameters (*16*). As the forward model of this backcalculation method, the generalized Westergaard model was used which accounts for the inertia and damping effects of foundation as well as the viscoelasticity of the plate (*16*). By performing a field study on two FWD deflection basins obtained from adjacent rigid and flexible pavements in Minnesota, it was shown that including both inertia and damping effects of foundation is substantial for accurate description of the behavior of both rigid and flexible pavements under dynamic loading. Therefore, in order to obtain realistic estimations for the dissipated energy, the deflection-induced PVI model proposed by Louhghalam et al. needs to be modified to account for foundation inertia and damping.

The purpose of this paper is to demonstrate how FWD measurements can be used by transportation agencies to evaluate deflection-induced vehicle fuel consumption. To this end, the PVI analysis is modified first to account for inertia and damping effects of the layers underlying the road surface. This modification makes the analysis compatible with the generalized Westergaard model. Next, one flexible and one rigid pavement section are selected from the database provided by the Long Term Pavement Performance (LTPP) program, each of which were tested multiple times at different months of a year. The model parameters were backcalculated for the selected pavement sections, and then employed as inputs to estimate the resulting fuel consumption. The variation in energy dissipation due to seasonal changes was also studied. The results confirm that the proposed methodology can be a reliable tool to evaluate deflection-induced vehicle fuel consumption and environmental footprint.

THEORETICAL BACKGROUND

The plate-on-a-foundation model has been commonly used for structural modeling of rigid pavements. Westergaard (*17*) idealized the rigid slab as a thin elastic Kirchhoff-Love plate resting on a Winkler foundation, which is a combination of closely spaced, independent elastic linear springs. Various researchers emphasized the more complex behavior of the foundation and added a dashpot to the Westergaard model to account for viscoelastic behavior of foundation (*18*-*21*). Also, the importance of foundation inertia effects was pointed out (*22*). Khazanovich demonstrated that the integrated inertia and damping effect can more accurately explain the behavior of pavement under dynamic loading, in particular, the time shift between the applied FWD load and the recorded deflection peaks (*23*). In a recent study, Khazanovich & Booshehrian proposed a generalized Westergaard model to account for viscoelasticity of the plate and the inertia and damping effects of foundation. They were able to show this model could accurately capture the pavement behavior under dynamic FWD loading for both flexible and rigid pavements (*16*).

The generalized Westergaard model consists of an infinite viscoelastic plate resting on a foundation that takes into account inertia and damping effects of the foundation (FIGURE 1). The plate is modeled with a three-parameter standard linear solid (SLS) model to capture the viscoelastic behavior of flexible pavement. The damping and inertia effects of foundation are accounted for by the addition of dashpot and mass elements to the Winkler foundation. The mass element represents the mass of the plate and the moving portion of the underlying layers under applied dynamic loads. The combination of the spring and dashpot simulates the viscoelastic behavior of the underlying layers based on the Kelvin-Voigt model.

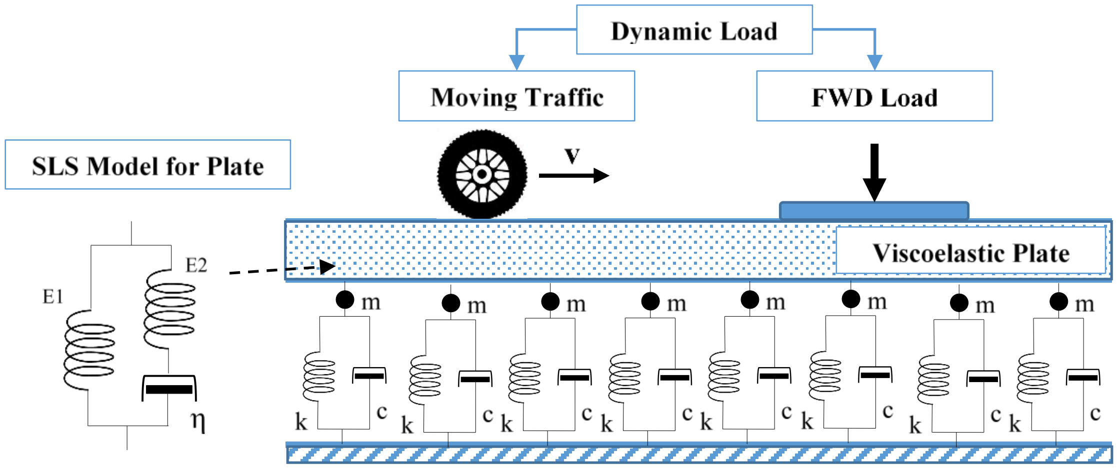

FIGURE 1 Generalized Westergaard Model

In the following section, the generalized Westergaard model is incorporated into the PVI frameworks (*11*,*15*).

Deflection-Induced PVI Model

Consider an infinite plate subjected to a moving load $P = pS$ representing the wheel load, with S rectangular area of tire-road contact trajectory. Herein, we consider a moving coordinate system $X = x - Vt$, attached to the load traveling with constant speed V. For any viscoelastic material in this reference frame, one can show that the dissipated energy within the material is related to the slope in the moving direction at the road-tire contact trajectory (*12*). Assuming a uniformly distributed load, the dissipated energy per distance traveled, δU, reads:

$$\delta U = -P \left\langle \frac{dw}{dX} \right\rangle \tag{1}$$

where w is the plate deflection and $\langle dw/dX \rangle$ is the average slope along the area of tire-road contact surface in X-direction. Hence, to evaluate the energy dissipation one needs to evaluate plate deflection and its spatial derivative in the moving coordinate system. Herein, we employ the elastic-viscoelastic correspondence principle (*24-26*) to evaluate deflection. The principle allows for finding the solution of a viscoelastic problem from the solution of a corresponding elastic problem in the frequency domain, by substituting the complex modulus of the viscoelastic material with its elastic counterpart.

Using the elastic-viscoelastic correspondence principle, first the solution to equation of motion of an elastic plate on an elastic foundation subjected to a moving load needs to be obtained in the frequency domain. Assuming a steady-state condition (constant speed), and noting that in the moving coordinate system $\partial/\partial t = -V\partial/\partial X$, the equation of motion in this reference frame reads:

$$D\left(\frac{\partial^2}{\partial X^2} + \frac{\partial^2}{\partial y^2}\right)^2 w + mV^2 \frac{\partial^2 w}{\partial X^2} + kw = p \tag{2}$$

where $D = Eh^3/12(1-\nu^2)$ is plate's instantaneous flexural stiffness and m is mass per unit area of the plate and moving portion of foundation; E, h, and ν are instantaneous modulus of elasticity, thickness, and Poisson's ratio of the surface layer (plate), respectively. Taking the Fourier transformation of the above solution in frequency domain gives:

$$\hat{w} = \hat{p}\,(D(\lambda_1^2+\lambda_2^2)^2 - mV^2\lambda_1^2 + k)^{-1} \tag{3}$$

where λ_1 and λ_2 are respectively the transformed fields of X and y.

To find the solution of a viscoelastic plate on a viscoelastic foundation, the following approach was taken. The stress-strain relationship of the viscoelastic top layer is according to the constitutive equation of a standard linear solid (SLS) model (illustrated in the inset of FIGURE 1).

$$\frac{\partial \varepsilon}{\partial t} = \frac{1}{E_1+E_2}\left(\frac{\partial \sigma}{\partial t} + \frac{1}{\eta}(E_2\sigma - E_1E_2\varepsilon)\right) \tag{4}$$

where E_1, E_2 are two stiffness parameters of the model. In addition, η is the material viscosity parameter, and therefore, $\tau = \eta/E_2$ is the relaxation time of the viscoelastic top-layer. Damping of foundation is modeled via a Kelvin-Voigt viscoelastic foundation with stiffness k and relaxation time $\tau_s = c/k$, where c is viscous damping coefficient of foundation as illustrated in FIGURE 1. To incorporate the viscoelasticity of foundation, the elastic foundation modulus k is replaced with the complex modulus of a Kelvin-Voigt model in the moving coordinate system, i.e. $\hat{k} = k(1 - i\lambda_1 V\tau_s)$.

For the SLS model representing the material of surface layer (plate), we first rewrite equation (4) in the moving coordinate system:

$$-V\frac{d\varepsilon}{dX} = \frac{1}{E_1+E_2}\left(-V\frac{d\sigma}{dX} + \frac{1}{\eta}(E_2\sigma - E_1E_2\varepsilon)\right) \tag{5}$$

Here we assume a three-dimensional creep behavior characterized by constant creep Poisson's ratio such that $\hat{D} = \hat{E}h^3/12(1-\nu^2)$. Then, taking Fourier transform of equation (5), the complex modulus can be obtained $\hat{D} = D_1(1 - i\lambda_1 V\tau(D_2/D_1 + 1))/(1 - i\lambda_1 V\tau)$ where $D_1 = E_1h^3/12(1-\nu^2)$ and $D_2 = E_2h^3/12(1-\nu^2)$. The solution for the viscoelastic problem in the frequency domain is expressed as:

$$\hat{w} = \hat{p}\left(\frac{1 - i\lambda_1 V\tau(D_2/D_1 + 1)}{1 - i\lambda_1 V\tau} D_1(\lambda_1^2+\lambda_2^2)^2 - mV^2\lambda_1^2 + k(1 - i\lambda_1\tau_s)\right)^{-1} \tag{6}$$

The viscoelastic plate deformation is obtained by taking the inverse Fourier transformation of above equation. The slope dw/dX is also similarly calculated from $\mathcal{F}^{-1}(-i\lambda V\hat{w})$ with $\mathcal{F}^{-1}$ denoting the inverse Fourier transformation.

The procedure above offers a computationally efficient approach for determining pavement deflections and energy dissipation under a moving load using the generalized Westergaard model. However, to ensure that the estimation of the energy dissipation is realistic, it is important to select appropriate values for model parameters that will result in calculated deflections similar to those exhibited by the pavement system. These quantities can be obtained from the dynamic backcalculation analysis of FWD data as explained below.

Dynamic Backcalculation of Pavement Parameters Using FWD Data

FWD measures the time histories of the applied load and surface deflections at different distances from the center of a circular FWD applied pressure. Thus the governing differential equation for an infinite, homogeneous, isotropic, and linearly viscoelastic plate on a viscoelastic foundation subjected to axisymmetric FWD loading is:

$$D'\left(\frac{1}{r}\frac{\partial}{\partial r}+\frac{\partial^2}{\partial r^2}\right)^2 w(r,t)+k\,w(r,t)+c\frac{\partial w(r,t)}{\partial t}+m\frac{\partial^2 w(r,t)}{\partial t^2}=p(r,t) \qquad (7)$$

where D' is the viscoelastic rigidity of the plate that can be calculated based on stress-strain relationship of the viscoelastic top layer given in equation (4), $w(r,t)$ is the surface deflection, $p(r,t)$ is the applied pressure in the FWD test, r is the distance from the center of FWD load, and *t* is the time. The pressure, $p(r,t)$, is obtained from measurements in the FWD tests, and is not necessarily a mathematical function, therefore equation (7) must be solved numerically. Khazanovich & Booshehrian (*16*) proposed a numerical solution for this equation using a combined application of Hankel transform in space and finite difference method in time. Taking advantage of the time domain approach prevents the potential problems of using frequency domain such as the need for tail correction (*27*-*29*).

The obtained semi-analytical solution is used as a forward solution in the backcalculation procedure. A normalized sum of squared errors (SSE) is defined to quantify the difference between the measured and calculated FWD deflections. A combination of quasi-Newton method and a finite-difference gradient is employed to find the solution to the inverse problem, which is to find the set of parameters that minimizes the following error function.

$$SSE=\left(\frac{1}{w_{max}^{M}}\right)^2\sum_{i=1}^{n}\sum_{j=1}^{m}\left(w_{ij}^{M}-w_{ij}^{C}\right)^2 \qquad (8)$$

where *n* is the number of sensors, *m* is the number of time steps in the FWD deflection time history, w_{ij}^{M} and w_{ij}^{C} are the measured and calculated deflections for sensor *i* at time *j*, respectively, while w_{max}^{M} is the maximum measured deflection in the FWD deflection history. The error is normalized by dividing by w_{max}^{M}, so that their non-dimensional SSE values can be compared. The parameters to be determined from the backcalculation procedure are 1) the plate's instantaneous flexural stiffness, *E*, 2) the ratio E_1/E, and 3) the relaxation time of the plate material, τ, 4) foundation stiffness ,k, 5) foundation inertia ,m, and 6) damping coefficient of the foundation, c.

CASE STUDY

The previous section describes how the pavement-vehicle interaction (PVI) model was modified according to the generalized Westergaard model to account for inertia and damping effects of underlying layers. This section illustrates how the model parameters, backcalculated using the FWD data, can be used in the implementation of the PVI model to estimate the vehicle fuel consumption due to pavement deformation for both rigid and flexible pavements. This section also examines if the developed procedure is able to address the seasonal variations in pavement system and provide acceptable estimations of fuel consumption. Especially when considering flexible pavements fabricated with a hot mix asphalt (HMA) course as the surface layer, temperature variation could considerably influence the viscoelastic properties of the asphaltic material, and thus, the amount of energy dissipated through PVI.

The FWD data collected through the "Seasonal Monitoring Program (SMP)" of the Long Term Pavement Performance (LTPP) program were used in this study (*30*). The SMP study did not contain a set of flexible and rigid pavements located in fairly similar locations, so pavements with relatively similar sublayers were chosen: a flexible pavement located in Nevada (ID = 320101) and a rigid pavement located in North Carolina (ID = 370201). Both sections were in good condition in year 2000. Details of the pavement sections are described in Table 1.

TABLE 1 Detailed Information on the Selected Pavement Sections

Location / Section ID	Pavement Type	Surface Layer	Thickness (m) / Density (kg/m^3)	Base layer / Thickness (m)	Subbase layer / Thickness (m)	Subgrade Type
NV / NV0101	Flexible	HMA	0.1829 / 2234	Agg. / 0.208	Agg./ 0.579 + Treated/ 0.305	Coarse Grained
NC / NC0201	Rigid	PCC	0.2337/ 2240	Agg. / 0.236	Treated/ 0.203	Fine Grained

A Poisson's ratio of 0.15 was assumed for the rigid pavement and 0.35 for the flexible pavement. FWD tests were performed at the center of the slab, away from the pavement edge (J1 loading). The same location of the pavement section was investigated at different times of the year. Further information on the two sections studied here can be found on InfoPave™, the online LTPP database (*30*).

RESULTS

Six FWD deflection measurements for the flexible section (NV0101) and five FWD deflection measurements for the rigid section (NC0201) collected in year 2000 were used for this study. The sections were analyzed using the dynamic backcalculation procedure described in the previous section (*16*) and the results are summarized in Table 2 along with the month and surface temperature of the FWD testing. The backcalculated parameters were then used to calculate the deflection basins. The time history of measured and calculated surface deflections at different sensor locations (0.0 to 1.5 m) are shown in Figures 2 (sections NV0101) and 3 (section NC0201).

The backcalculated model parameters were ultimately used in the modified PVI model to compute the dissipated energy and fuel consumption under a moving vehicle load. The analysis was performed at typical highway speed of 100 Km/hr for an HS-20 (a 20 ton semi-trailer truck). The tire-road contact surface was assumed to be a square with dimension of 0.15 x 0.15 m. The dissipated energy per distance traveled was calculated based on equation (1). The associated fuel consumption is obtained by dividing the dissipated energy by the energy content of fuel which is equal to 38.74 MJ/liter for Diesel (*1*). The results of this analysis are summarized in Table 3 together with the month and surface temperature at the time of FWD tests.

TABLE 2 Backcalculated Pavement Parameters Based on the FWD Deflection Basins

Pavement Type	ID	Month	Surface Temp.	Foundation Parameters			Plate Parameters			Error
				k	m	c	E	E1/E	τ	
			˚C	KPa/mm	kg/m²	Ns/m/m²	GPa	-	s	-
Flexible (NV0101)	A1	Feb	1.4	92.83	1102.2	7.07E+05	26.53	1.00	-	6.98
	B1	Mar	16.5	92.93	822.2	7.08E+05	22.05	1.00	-	7.04
	C1	May	18.2	96.50	662.0	6.87E+05	18.95	0.93	4.95	6.71
	D1	Aug	34.9	143.59	408.8	7.77E+05	8.63	0.51	2.28	9.41
	E1	Sep	23.7	102.87	408.8	7.31E+05	13.90	0.81	6.31	7.50
	F1	Nov	3.9	91.24	998.3	6.64E+05	23.80	1.00	-	7.25
Rigid (NC0201)	B1	Feb	11.2	32.46	838.2	3.47E+05	34.73	1.00	-	1.88
	C1	Mar	13.8	34.25	1158.7	3.98E+05	34.93	1.00	-	2.44
	E1	May	26.5	30.09	1529.9	3.59E+05	33.80	1.00	-	6.81
	F1	Aug	36.2	30.16	1308.0	3.52E+05	33.17	1.00	-	3.07
	G1	Sep	32.7	32.46	963.9	3.75E+05	33.83	1.00	-	2.73

TABLE 3 Results of Energy Dissipation Analyses Using the Backcalculated Pavement Parameters

Pavement Type	ID	Month	Surface Temp.	Dissipation Rate	Dissipation	Fuel Consumption
			˚C	(J/Sec)	(MJ/Km)	(Gal/mile)
Flexible (NV0101)	A1	Feb	1.4	163.22	5.88E-03	6.45E-05
	B1	Mar	16.5	195.82	7.05E-03	7.74E-05
	C1	May	18.2	212.14	7.64E-03	8.38E-05
	D1	Aug	34.9	362.40	1.30E-02	1.43E-04
	E1	Sep	23.7	293.28	1.06E-02	1.16E-04
	F1	Nov	3.9	173.23	6.24E-03	6.84E-05
Rigid (NC0201)	B1	Feb	11.2	87.61	3.15E-03	3.46E-05
	C1	Mar	13.8	108.11	3.89E-03	4.27E-05
	E1	May	26.5	103.80	3.74E-03	4.10E-05
	F1	Aug	36.2	101.94	3.67E-03	4.03E-05
	G1	Sep	32.7	104.60	3.77E-03	4.13E-05

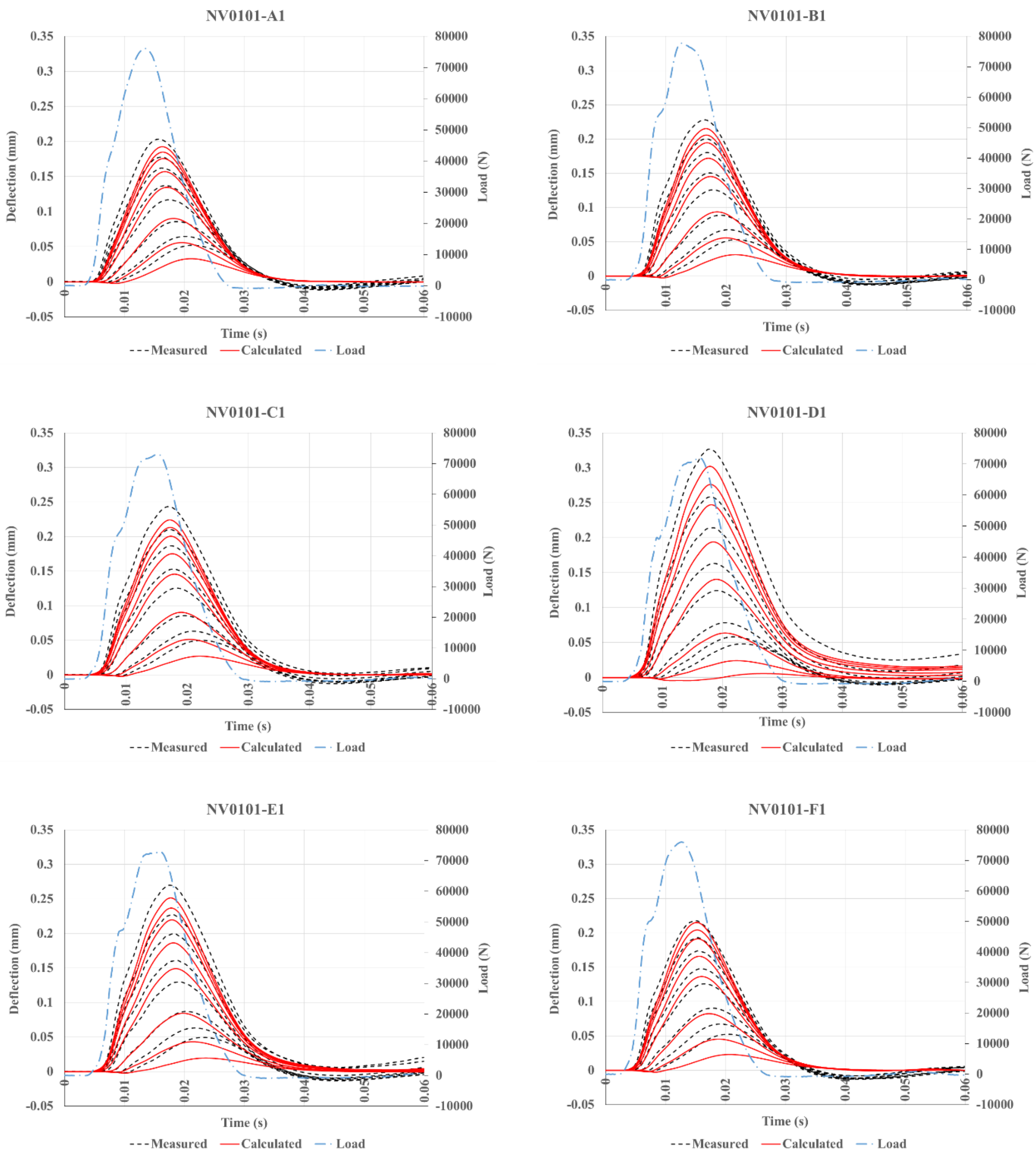

FIGURE 2 Measured and Calculated FWD Deflection Basins for Flexible Pavement (NV0101) in Nevada at Different Months

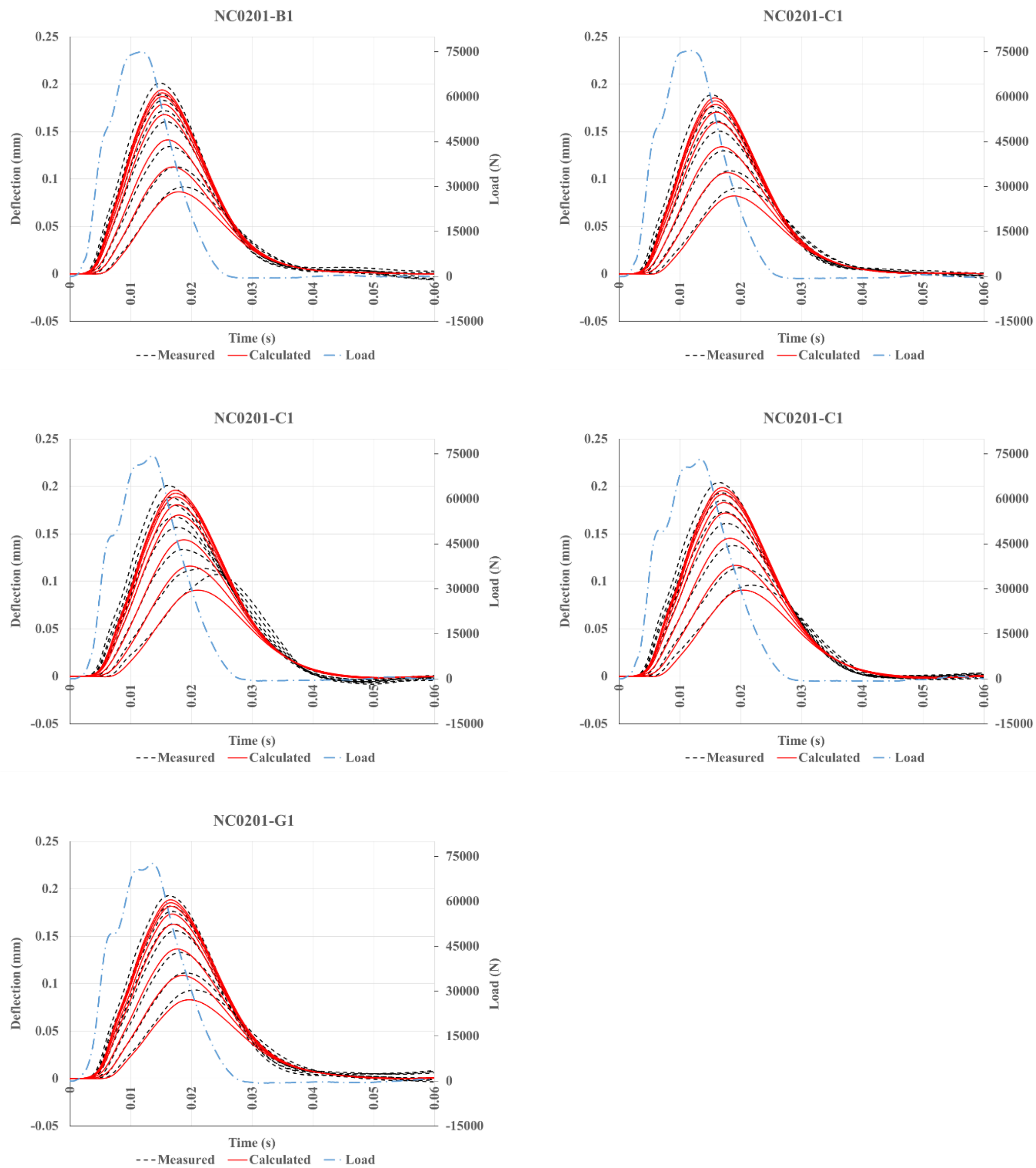

FIGURE 3 Measured and Calculated FWD Deflection Basins for Rigid Pavement (NC0201) in North Carolina at Different Months

DISCUSSION

The backcalculated pavement parameters are reliable if the measured and calculated FWD deflection basins are in close agreement with each other, confirming that the backcalculated parameters are capable of appropriately describing the pavement behavior under dynamic loading. The agreement of the measured and calculated results illustrated in Figures 2 and 3 indicates that the proposed method is an effective tool for evaluating the properties of pavement sections.

The results of the analyses on the SMP sections (NV0101 and NC0201), shown in Table 2, reveals that the properties of the PCC layer in the selected rigid pavement remained almost constant and the PCC plate behaved elastically regardless of the seasonal/temperature variations. The foundation properties, except for foundation viscosity exhibited relatively higher variability, in particular the foundation inertia effect. On the other hand, for flexible pavement, the temperature variation and seasonal changes caused considerable changes in the properties of both the plate (HMA course) and the foundation (underlying layers). Both coefficients of subgrade reaction and foundation inertia effect varied significantly with the temperature change while the foundation viscosity did not encounter significant changes. The instantaneous elastic modulus of the HMA plate altered proportionally with the surface temperature change. The plate behaved elastically at the colder periods of the year (Feb, Mar, and Nov) and became more viscous as the temperature increased. The obtained backcalculated parameters were in line with the expectations of the behavior of rigid and flexible pavements.

Figure 4 depicts the variation of fuel consumption and testing temperature throughout the year 2000. Figure 4 clearly demonstrates the dependency of the vehicle energy consumption on the temperature change for flexible pavements. An increase in the temperature made the HMA surface more viscous, resulting in more viscoelastic deformation and a higher amount of deflection-induced dissipation of energy. In contrast, based on the backcalculated plate parameters, shown in Table 2, the PCC layer behaved elastically regardless of the seasonal variation, and the dissipation due to the plate deformation is insignificant. Interestingly, the consumed fuel for rigid pavements plotted in Figure 4 was a consequence of viscoelastic properties of the underlying layer and not the surface layer. The backcalculated damping coefficient of foundation showed minor variation in the pavement section in North Carolina (see Table 2), which made the vehicle fuel consumption independent from temperature variation for the selected rigid pavement in this region. It is important to note that the fuel consumption caused by foundation viscoelasticity might vary considerably in regions that encounter considerable seasonal variation in the soil properties.

Overall, based on the observations made in this study, the proposed method — dynamic backcalculation analyses using FWD time history data followed by the modified deflection-induced PVI analyses — provided reasonable results, which are in agreement with realistic expectations and field observations. Since FWD testing is a common pavement evaluation practice, the proposed method could be used widely to perform network scale analyses. The estimated deflection-induced energy dissipation and vehicle fuel consumption could potentially be incorporated as a factor in pavement management and in future network planning to reduce greenhouse gas (GHG) emissions and design more sustainable roads (*15*). It is necessary to note that the proposed approach still has to be tested and validated via field measurements of fuel consumption for various site conditions and pavement structures.

The proposed tool shows reasonable results for the sections analyzed in this study, yet the model can still benefit from improvement. A few possible improvements are discussed here.

The results in Figures 2 and 3 show that the discrepancy between the curves is smaller for the rigid section than for a relatively thick flexible pavement. One reason might be that the generalized Westergaard model employed in this study ignores the shear resistance of the underlying layers. While this assumption may be realistic for rigid pavements, it may not hold true for flexible pavements, especially when the top layer is thin. Thus, one important adjustment to the model could be including shear resistance in the foundation model, especially for flexible pavements. Making use of the Pasternak model could be a solution to this issue.

In addition, the viscoelastic Kirchhoff-Love plate adopted in this study does not account for shear deformation and compressibility of the surface layer, which might be important properties for HMA layers. However, these properties are more influential in flexible pavements constructed with thicker HMA layers as seen in full-depth asphalt pavements. Those pavements were not the topic of this study.

Another important factor to improve is accounting for the effect of daily temperature change on the properties of the flexible pavement and on fuel consumption. This effect could have considerable impact on estimating the use-phase GHG emissions. One solution for addressing this issue is to perform similar analyses on multiple sets of FWD tests conducted on the same day to capture the effect of daily temperature variation on the properties of pavement system, and to define/introduce correction factors.

It is worth noting that the PVI analysis herein assumes an infinite plate and does not consider the impact of joints spacing and characteristics on vehicle fuel consumption. Neglecting the joints impact might underestimate the deflection-induced energy dissipation for rigid pavements. However, this impact is local and can only be considerable at locations very close to the joints. Further investigation is required to quantify the variation in fuel consumptions close to the joints.

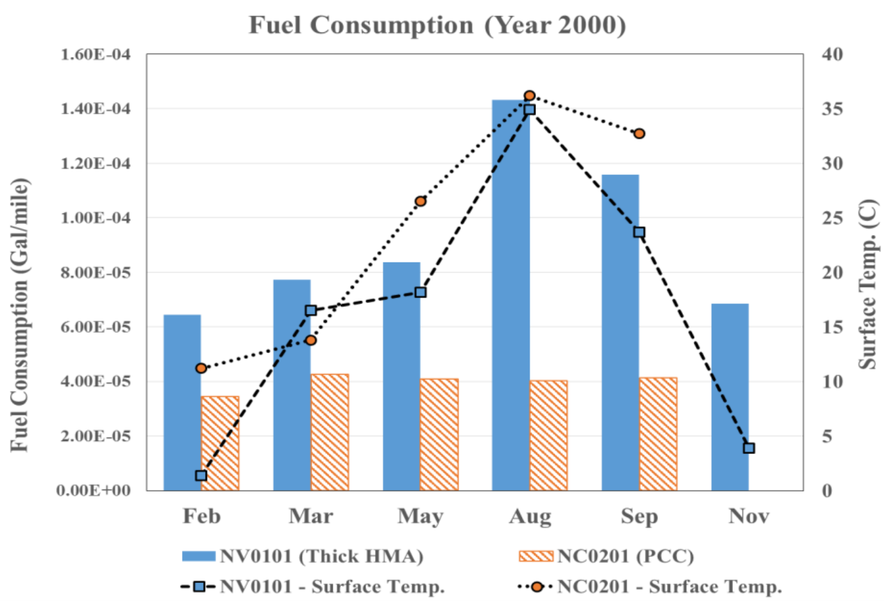

FIGURE 4 Effect of Seasonal Variation on the Dissipation Rate for both Flexible and Rigid Pavements

CONCLUSIONS

In this study, the structural parameters of the tested pavement sections are backcalculated by minimizing the difference between the time histories of deflections measured via FWD and the deflections calculated using the generalized Westergaard model. The backcalculated parameters are then used to estimate the vehicle fuel consumption due to deflection-induce pavement-vehicle interaction. The described procedure allows for establishing a link between the structural parameters of rigid and flexible pavements, and vehicle fuel consumption and greenhouse gas (GHG) emissions during the pavement use-phase. The purpose of this study is to show that the proposed method can be used to estimate the fuel consumption related to both asphalt and concrete pavements. Since the two tested pavement sections were not structurally equivalent, direct comparison is not possible. The following general conclusions can be drawn from this study:

- Modifying the PVI model to be compatible with the generalized Westergaard model allows it to take into account the impact of foundation damping and inertia.
- It is shown that the generalized Westergaard model is able to capture the behavior of both rigid and flexible pavements under dynamic loading with good accuracy, which makes the assignment of model parameter for PVI analysis more reliable.
- The proposed methodology is able to describe the pavement structural changes due to seasonal variation for the selected rigid and flexible pavement sections. The energy is dissipated through the viscous deformation of both the surface layer and underlying layers.
- Seasonal variations affects the amount of fuel consumption throughout a year for flexible pavement mainly due to the noticeable variation in the temperature and the corresponding change in viscoelastic properties of the HMA surface course.
- A significant portion of energy dissipation occurs in the foundation. Thus, ignoring this effect may lead to underestimation of the energy dissipation, especially for rigid pavements.
- The simplicity of the described model and the availability of FWD measurements makes the proposed methodology an attractive tool for performing network scale analyses and, potentially, for designing more sustainable roads.

Good fit was obtained in the performed analyses for the two tested pavement sections; however, there is still a room for improvement of the generalized Westergaard model, in particular for flexible pavements. One possible modification is to use a foundation model that incorporates the shear contribution of the foundation. The applicability of this model for a wider range of pavement systems and climatic conditions, such as a thin HMA layer, should be further investigated. The effect of daily temperature change on the viscoelastic properties of the HMA layer and energy dissipation must be evaluated in future studies. Further studies should investigate the contribution of joints spacing and joints characteristics to the energy dissipation.

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REFERENCES

1. Ardekani, S. A., and P. Sumitsawan. Effect of pavement type on fuel consumption and emissions in city driving, http://www.rmc-foundation...20Study%20Final%203-10.pdf, 2010
2. Gschsser, F., and H. Wallbaum. Life Cycle Assessment of Representative Swiss Road Pavements for National Roads with an Accompanying Life Cycle Cost Analysis. *Environmental Science & Technology*, Vol. 47, 2013, pp. 8453-8461.
3. Chatti, K., and I. Zaaber. Estimating the effects of pavement condition on vehicle operating costs. *NCHRP Report 720*. Transportation Research Board of the National Academies, Washington, D.C., 2012.
4. Louhghalam, A., Tootkaboni, M., and F. J. Ulm. Roughness-Induced Vehicle Energy Dissipation: Statistical Analysis and Scaling. *Journal of Engineering Mechanics*, 2015, 04015046.
5. Louhghalam, A., Akbarian, M., and F. J. Ulm, Roughness-induced pavement-vehicle interactions: Key parameters and impact on vehicle fuel consumption. *Accepted for publication in Transportation Research Record: Journal of the Transportation Research Board*, 2015.
6. Zaabar, I., and K. Chatti. Calibration of HDM-4 models for estimating the effect of pavement roughness on fuel consumption for US conditions. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2155, Transportation Research Board of the National Academies, Washington, D.C., 2010, pp. 105-116.
7. Zaabar, I., and K. Chatti. New mechanistic-empirical approach for estimating the effect of roughness on vehicle durability. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2227, Transportation Research Board of the National Academies, Washington, D.C., 2011, pp. 180-188.
8. Wang, T., Harvey, J., and A. Kendall. Reducing greenhouse gas emissions through strategic management of highway pavement roughness. *Environmental Research Letters*, Vol. 9, No. 3, 2014, 034007.
9. Pouget, S., Sauzéat, S., Benedetto, H.D., and F. Olard. Viscous energy dissipation in asphalt pavement structures and implication for vehicle fuel consumption. *Journal of Materials in Civil Engineering*, Vol. 24, No. 5, 2011, pp. 568-576.
10. Chupin, O., Piau, J. M., and A. Chabot. Evaluation of the structure-induced rolling resistance (SRR) for pavements including viscoelastic material layers. *Journal of Materials and structures*, Vol. 46, No. 4, 2013, pp. 683-696.
11. Pouget, S., Sauzéat, S., Benedetto, H.D., and F. Olard. Calculation of viscous energy dissipation in asphalt pavements. *Baltic Journal of Road and Bridge Engineering*, Vol. 9, No. 2, 2014, pp. 123-130.
12. Louhghalam, A., Akbarian, M., and F. J. Ulm. Flügge's Conjecture: Dissipation-versus Deflection-Induced Pavement–Vehicle Interactions. *Journal of Engineering Mechanics*, Vol. 140, No. 8, (04014053), 2013.
13. Louhghalam, A., Akbarian, M., and F. J. Ulm. Scaling relations of dissipation-induced pavement-vehicle interactions. *Transportation Research Record, Journal of the Transportation Research Board*, No. 2457, Transportation Research Board of the National Academies, Washington, D.C., 2014, pp. 95-104.

14. Louhghalam, A., Akbarian, M., and F. J. Ulm. Pavement Infrastructures Footprint: The Impact of Pavement Properties on Vehicle Fuel Consumption, *Proceedings of Computational Modelling of Concrete Structures*. EURO-C, 2014.
15. Louhghalam, A., Akbarian, M., and F. J. Ulm. Carbon Management of Infrastructure Performance: Integrated Big Data Analytics and Pavement-Vehicle-Interactions, *under review*, 2015.
16. Khazanovich, L., and A. Booshehrian. Dynamic visco-elastic analysis of falling weight deflectometer deflections for rigid and flexible pavements. *Accepted for publication in Transportation Research Record: Journal of the Transportation Research Board*, 2015.
17. Westergaard, H. M. Stresses in concrete pavements computed by theoretical analysis. *Public Roads*, Vol. 7, No. 2, 1926, pp. 25-35.
18. Kim, Y., and Y. R. Kim. Prediction of layer moduli from falling weight deflectometer and surface wave measurements using artificial neural network. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1639, Transportation Research Board of the National Academies, Washington, D.C., 1998, pp. 53-61.
19. Kutay, M. E., Chatti, K., and L. Lei. Backcalculation of Dynamic Modulus Mastercurve from Falling Weight Deflectometer Surface Deflections. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2227, Transportation Research Board of the National Academies, Washington, D.C., 2011, pp. 87-96.
20. Kuo, C. M., and T. Y. Tsai. Significance of subgrade damping on structural evaluation of pavements. *Road Materials and Pavement Design*, Vol. 15, No. 2, 2014, pp. 455-464.
21. Kuo, C. M., Lin, C. C., Huang, C. H., and Y. C. Lai. Issues in simulating falling weight deflectometer test on concrete pavements. *KSCE Journal of Civil Engineering*, 2015, pp. 1-7.
22. Sebaaly, B. E., Mamlouk, M. S., and T. G. Davies. Dynamic analysis of falling weight deflectometer data. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1070, Transportation Research Board of the National Academies, Washington, D.C., 1986, pp. 63-68.
23. Khazanovich, L. Dynamic analysis of FWD test results for rigid pavements. *Symposium on Nondestructive Testing of Pavements and Backcalculation of Moduli*, ASTM STP 1375, American Society for Testing and Materials, West Conshohocken, PA, Vol. 3, 2000, pp. 398-411.
24. Pozhuev, V. Steady-state reaction to the effect of a moving load in a system consisting of a cylindrical shell and a viscoelastic filler, *International Journal of Applied Mechanics.* Vol. 22, No. 5, 1986, pp. 415–421.
25. Read, W. T. Stress analysis for compressible viscoelastic materials. *Journal of Applied Physics*, Vol. 21, No. 7, 1950, pp. 671–674.
26. Christensen, R. Theory of viscoelasticity: An introduction, *Academic Press*, New York, 1982.
27. Uzan, J. Dynamic linear back calculation of pavement material parameters. *Journal of transportation engineering*, Vol. 120, No. 1, 1994, pp. 109-126.
28. Chatti, K. Use of Dynamic Analysis for Interpreting Pavement Response. *Materials Evaluation*, Vol. 62, No. 7, 2004, pp. 764–774.
29. Zaabar, I., Chatti, K., Lee, H. S., and N. Lajnef. Backcalculation of asphalt concrete modulus master curve from field measured falling weight deflectometer data using a new time domain

viscoelastic dynamic solution and genetic algorithm. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2475, Transportation Research Board of the National Academies, Washington, D.C., 2014, pp. 80-92.

30. FHWA, U.S. Department of Transportation. LTPP: Long-Term Pavement Performance Program. http://www.infopave.com/ Accessed 2015.