Load spatial superposition effect in Traffic Speed Deflectometer tests of pavements

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ABSTRACT: Devices that can evaluate the structural health of pavements at traffic speeds, such as the Traffic Speed Deflectometer (TSD), have become increasingly popular because of their high measuring efficiency. Concurrently, there has been a growing body of research focused on the theoretical understanding and practical application of the TSD test. However, few studies have considered the load spatial superposition effect when conducting theoretical modelling of the TSD test, which introduces errors in the parameter identification process. Hence, this study investigated the effect of load spatial superposition on pavement response during the TSD test using a self-developed software called PaveMove. The results showed that, for pavements with flexible base, the TSD deflection-based parameter identification requires the consideration of the whole TSD load, while the TSD slope-based parameter identification has more degrees of freedom in the choice of load patterns. In contrast, for pavements with (semi-)rigid base, both the TSD deflection- and slope-based parameter identifications require the consideration of the whole TSD load. The presented work paves the way to develop more accurate parameter identification techniques for the TSD test, which ultimately contributes to more effective management of road networks.

1 INTRODUCTION

Effective pavement management is important to maintain the performance of pavements with minimum investments. To effectively manage road networks, accurate structural health information of pavements is necessary. A promising approach to obtain the structural health information is to non-destructively measure pavement surface response by using traffic speed deflection devices, such as the Traffic Speed Deflectometer (TSD). With the increasing application of the TSD test, corresponding theoretical and practical studies are becoming more and more popular. However, in the theoretical modelling process, it is common to only consider the measuring wheel of the TSD device, while neglecting the effect of other wheels on pavement response. This simplification inevitably introduces errors in the process of parameter identification of pavements based on TSD measurements. The identified parameters with errors could lead to inaccurate maintenance and rehabilitation plans of road networks. To solve this problem, this study focuses on the load spatial superposition effect in the TSD test to draw the attention of researchers. This work helps formulate more accurate parameter identification techniques for the TSD test and contributes to more effective management of pavements.

2 THEORETICAL MODELLING OF TSD TESTS

In the TSD test of pavements, a truck equipped with sensors is used to measure the surface response of pavements caused by moving wheel loads. There are two important loading axles on the TSD device, and each axle has a pair of tires at each end. In the process of theoretical modelling, the pavement was considered as a structure with multiple layers, and the TSD load was considered as a uniform load that moves on the surface of the structure with a constant speed. Subsequently, a Spectral Element Method-based procedure shown in Sun et al. (2019) was followed to develop a theoretical model for the TSD test, which was implemented into a computer programme called PaveMove. In the PaveMove software, the number of pavement layers, the properties of each layer, and the loading configuration can be defined by users. Each pavement layer can be considered to be purely elastic, elastic with hysteretic damping, or viscoelastic. In addition, the applied load can be a pair of tires (1/2 axle), two pairs of tires (1 axle), or four pairs of tires (2 axles); each tire has a constant pressure and a rectangular contact area with the pavement surface.

To simulate the effect of hysteretic damping, the following complex Young's modulus $\hat{E}(\omega)$ defined in the frequency domain was used:

$$\hat{E}\left(\omega\right)=E\left[1+2\mathrm{i}\xi\,\mathrm{sgn}\left(\omega\right)\right] \tag{1}$$

where E is the Young's modulus, i is the imaginary unit satisfying $\mathrm{i}^2=-1$, ξ is the damping ratio, sgn(·) is the signum function, and ω is the angular frequency. It should be noted that the damping ratio can be set to zero to simulate the behaviour of purely elastic materials. In addition, for viscoelastic materials, the frequency domain-defined complex Young's modulus $\hat{E}(\omega)$ of the 2S2P1D model was used (Sun et al., 2022):

$$\hat{E}\left(\omega\right)=E_0+\frac{E_\infty-E_0}{1+\zeta\left(\mathrm{i}\omega\tau\right)^{-k_p}+\left(\mathrm{i}\omega\tau\right)^{-h_p}+\left(\mathrm{i}\omega\tau\beta\right)^{-1}} \tag{2}$$

in which E_0 is the static modulus, E_∞ is the glassy modulus, k_p and h_p are dimensionless exponents with the relationship $0<k_p<h_p<1$, ζ is a positive dimensionless constant, τ is the characteristic time that depends only on temperature, and β is a dimensionless constant.

The calculation of pavement response caused by TSD loads is basically a moving load problem, which is more convenient to be solved in a coordinate system that moves along with the TSD device. In this moving coordinate system, the response of some fixed points is measured by sensors installed on the TSD.

3 MODEL VALIDATION

After the development of the PaveMove software, its performance to simulate the TSD test of pavements still needs to be validated. Hence, a case study corresponding to the Figure 3 in the reference Nielsen (2019) was considered for model validation. In PaveMove, the following parameters are used to simulate the TSD load:

- The driving speed of the TSD device is 22.2 m/s (80 km/h);
- The magnitude of the tire pressure is 800 kPa;
- Each tire has a rectangular contact area with the pavement surface, the dimensions of the contact area are 0.1276 m times 0.24 m;
- A pair of tires is used, the distance between the two tires is 0.11 m.

The configuration and loads of axles are the same as those shown in Sun et al. (2023). In addition, the structural parameters of the considered pavement are shown in Table 1.

Table 1. Structural parameters of the considered pavement.

Layers	E	ξ	v	ρ	h
	MPa	–	–	kg/m^3	m
Surface	5000	0.25	0.35	2000	0.1
Base	400	0.15	0.35	2000	0.3
Subgrade	100	0.10	0.35	2000	∞

Note: E is Young's modulus, ξ is damping ratio, v is Poisson's ratio, ρ is density, and h is thickness.

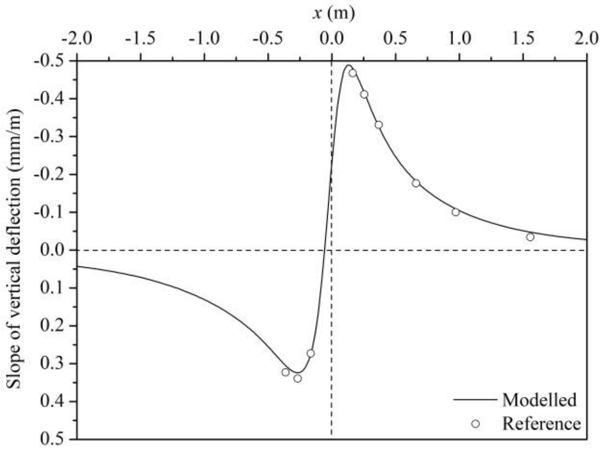


Figure 1. Results of model validation.

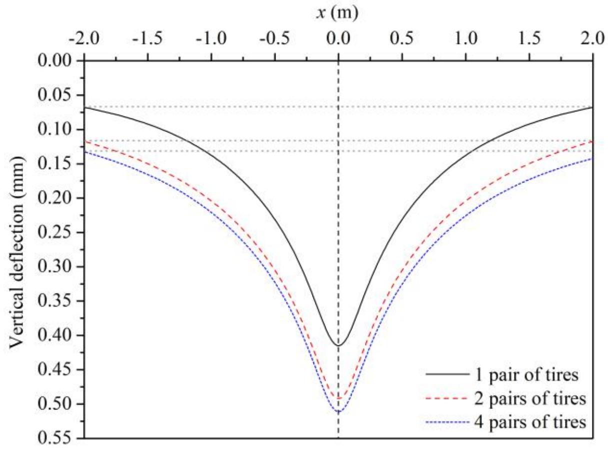
The results calculated by PaveMove were compared with the synthetic slope measurements presented in the reference, as shown in Figure 1. It can be seen that the results match well with each other, which validates the good performance of the developed PaveMove software.

4 LOAD SUPERPOSITION EFFECT IN TSD TESTS ON PAVEMENTS WITH FLEXIBLE BASE

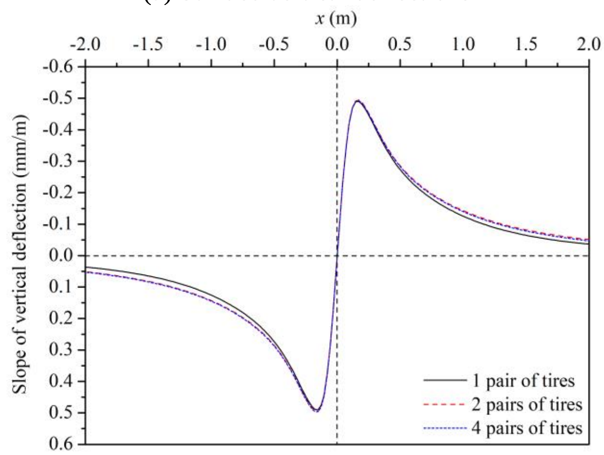
A commonly used type of pavements is pavements with flexible base. Hence, the load superposition effect in the TSD test on this type of pavements is investigated in this section. Results obtained from a purely elastic model and a viscoelastic model are presented.

4.1 *Purely elastic model*

In this part, a purely elastic model was used to simulate a pavement with flexible base. For this pavement, the Young's modulus of the surface layer is 3000 MPa, the damping ratios of all layers are zero, and other structural parameters are the same as those shown in Table 1. The calculated surface vertical deflections and corresponding slopes are shown in Figure 2.



(a) Surface vertical deflections



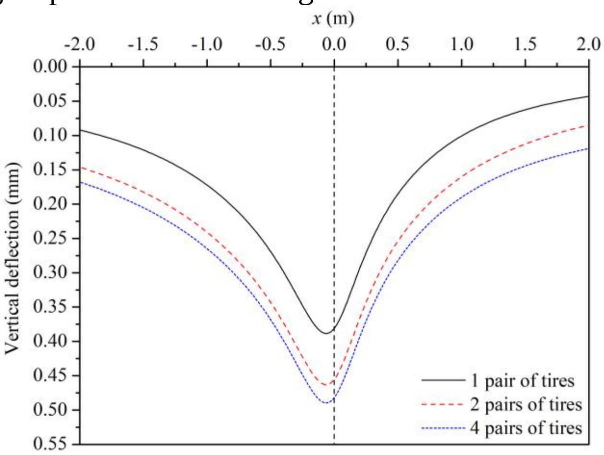
(b) Slopes of surface vertical deflections

Figure 2. Results obtained from the purely elastic model for the pavement with flexible base.

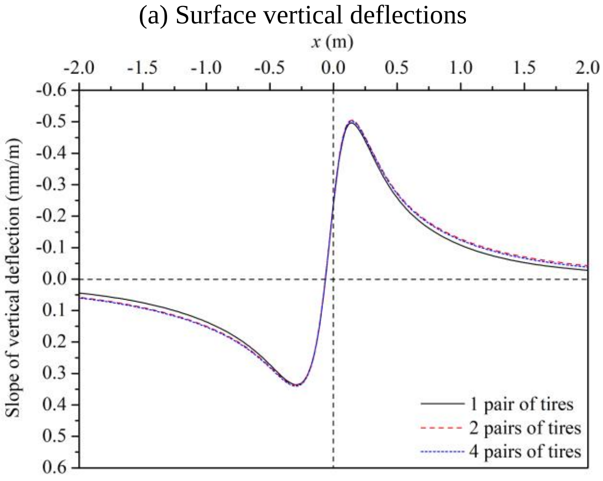
The results show that the load superposition effect is significant for vertical deflections under the TSD measuring wheel, especially the superposition effect caused by the pair of tires on the same axle. However, the load superposition has a slight effect on the slopes of vertical deflections. These results indicate that, if vertical deflections are used for parameter identification, the use of the whole TSD load in theoretical modelling is necessary to reduce errors in identified parameters. However, if slopes of vertical deflections are used for parameter identification, the use of the whole TSD load or not will cause a slight difference in identified parameters. It is also found that vertical deflections obtained from purely elastic model become asymmetric when considering two axles because of load spatial superposition effect.

4.2 *Viscoelastic model*

In this part, a viscoelastic model was used to simulate a pavement with flexible base. For this pavement, the surface layer is considered to be viscoelastic, and its behaviour is simulated by using the 2S2P1D model with the following parameters: E_0 = 250 MPa, E_∞ = 45400 MPa, k_p = 0.175, h_p = 0.55, ζ = 2.0, τ = 3.855×10^{-4} s, and β = 320. Other parameters are the same as those shown in Table 1. The calculated surface vertical deflections and corresponding slopes are shown in Figure 3.



(a) Surface vertical deflections



(b) Slopes of surface vertical deflections

Figure 3. Results obtained from the viscoelastic model for the pavement with flexible base.

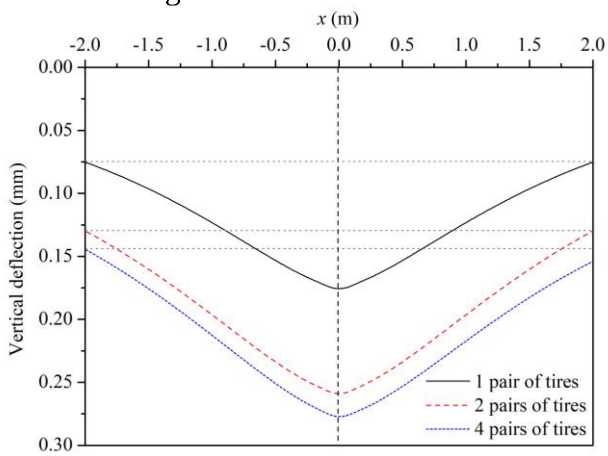
The results show that vertical deflections under TSD measuring wheel have the maximum value behind the wheel centre and decrease quicker in front of the wheel. This asymmetry is caused by both the damping effect and the load spatial superposition effect. The effect of load spatial superposition on vertical deflections and corresponding slopes is similar to the case of purely elastic model.

5 LOAD SUPERPOSITION EFFECT IN TSD TESTS ON PAVEMENTS WITH RIGID BASE

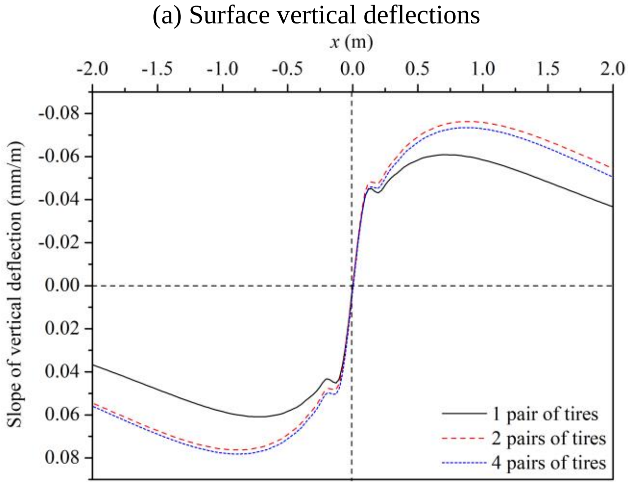
In engineering practice, when the traffic load is heavy and/or the subgrade is weak, the use of pavements with (semi-)rigid base is necessary (Sun et al., 2023). Hence, the load superposition effect in the TSD test on this type of pavements is studied in this section. The considered pavement has a rigid base with Young's modulus of 10000 MPa, while other parameters are the same as those used in Section 4 for different models.

5.1 *Purely elastic model*

In this part, a purely elastic model was used to simulate the pavement with rigid base. The calculated surface vertical deflections and corresponding slopes are shown in Figure 4.



(a) Surface vertical deflections



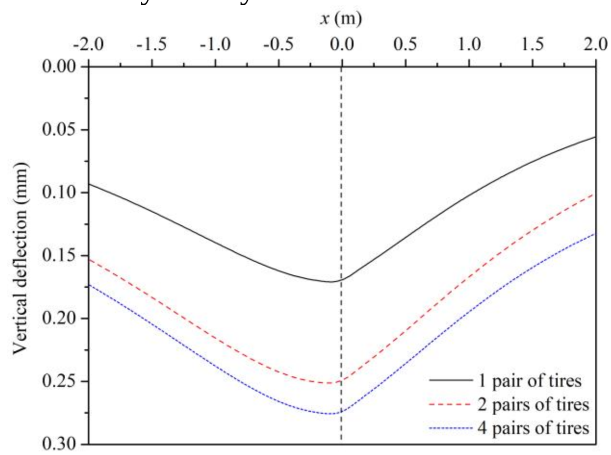
(b) Slopes of surface vertical deflections

Figure 4. Results obtained from the purely elastic model for the pavement with rigid base.

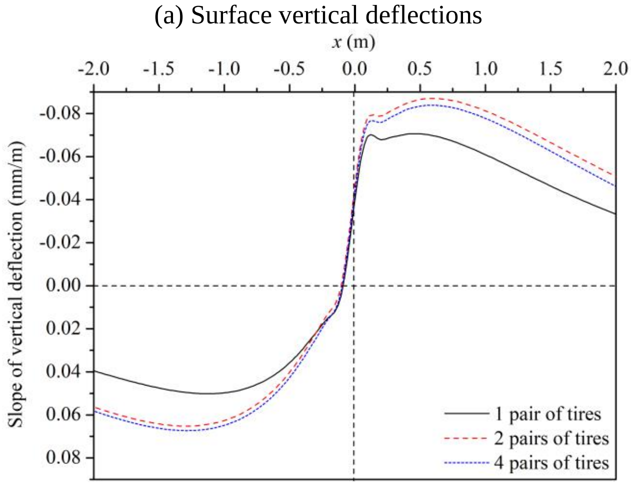
The results show that, compared with pavements with flexible base, the maximum vertical deflection of pavements with rigid base is smaller because of higher overall stiffness. Furthermore, vertical deflection curves of pavements with rigid base are “flatter” than pavements with flexible base. Moreover, slope curves of vertical deflections for the rigid base case are not as smooth as the flexible base case, which can cause difficulty in the process of parameter identification based on slopes. In addition, the load superposition has a significant effect on both vertical deflections and corresponding slopes, especially the effect caused by the pair of tires on the same axle as the TSD measuring wheel. Hence, to achieve accurate parameter identification based on vertical deflections or corresponding slopes of pavements with rigid base, the consideration of the whole TSD load is necessary. Similarly, the consideration of two axles also causes asymmetry in vertical deflections.

5.2 *Viscoelastic model*

In this part, a viscoelastic model was used to simulate the pavement with rigid base. The calculated surface vertical deflections and corresponding slopes are shown in Figure 5. The obtained results are similar to the case of purely elastic model except for the damping effect, which causes the delay of maximum values and asymmetry in vertical deflections.



(a) Surface vertical deflections



(b) Slopes of surface vertical deflections

Figure 5. Results obtained from the viscoelastic model for the pavement with rigid base.

6 CONCLUSIONS AND RECOMMENDATIONS

The Traffic Speed Deflectometer (TSD) test has emerged as a promising tool for efficient structural health evaluation of road networks, and corresponding research is increasing quickly. However, the theoretical modelling of the TSD test often only considers the measuring wheel while neglecting the load spatial superposition effect. This paper addresses this limitation by investigating the load spatial superposition effect in the TSD test. Based on the obtained results, the following conclusions can be drawn:

- For pavements with flexible base, the TSD deflection-based parameter identification requires the consideration of the whole TSD load, while the TSD slope-based parameter identification has more freedom in choosing load patterns.
- For pavements with (semi-)rigid base, both the TSD deflection- and slope-based parameter identifications require the consideration of the whole TSD load.

The presented work gives a better understanding of the load spatial superposition effect in the TSD test, which promotes the development of more accurate parameter identification techniques for the TSD test (or similar tests). In future work, it is recommended to formulate a parameter identification technique for the TSD test with robust practical performance, which can be further integrated into a digital twin of pavements to achieve more effective pavement management.

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