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EVALUATION OF PAVEMENT STRUCTURAL CONDITION USING FWD AND TSD MEASUREMENTS

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Abstract

Pavement condition assessment involves conducting tests and collecting data on the functional and structural condition of the pavement structure. Functional requirements refer to surface distresses, while structural requirements relate to the pavement's load-bearing capacity, that is, its ability to withstand a certain level of traffic loading. With the current trend towards evaluating structural condition using non-destructive testing methods, deflection measurement has become a common indicator of the structural behavior of pavements due to its simplicity. One of the most widely used non-destructive stationary testing devices for determining the structural capacity of pavements is the Falling Weight Deflectometer (FWD). In recent years, there has been growing interest in dynamic pavement deflection measurement methods that allow data collection at traffic speeds. The Traffic Speed Deflectometer (TSD) system represents modern technology that enables continuous measurement of pavement deflections. In this paper, pavement deflection measurements obtained on a selected highway section using the FWD and TSD devices will be compared. The analysis will include a comparison of characteristic parameters of the deflection basins, as well as a statistical correlation between the two methods. The expected outcome is that the results will contribute to a better understanding of the relationship between TSD and FWD measurements and to the assessment of TSD's potential as a faster method for continuous monitoring of the structural condition of pavement structures.

Key words: pavement condition assessment, structural capacity, deflections, FWD, TSD

1 Introduction

Pavement evaluation is conducted to determine the current condition of the pavement structure in terms of its functional and structural adequacy [1]. This process is essential for selecting appropriate and cost-effective surface treatments and for allocating limited funds and resources to maintain, rehabilitate and reconstruct pavement structures [2]. As the current trend is to collect pavement condition data using non-destructive testing methods, deflection measurement is becoming an increasingly popular way of evaluating pavement condition. The primary purpose of deflection testing is to determine the structural adequacy of existing pavement and to assess its capability to handle future traffic loadings. As observed in the early work by Hveem, there is a strong correlation between pavement deflections (an indicator of the structural adequacy of the pavement) and the ability of the pavement to carry traffic loadings at a prescribed minimum level of service [3]. The deflectometer method, which is one of the non-destructive tests, records the surface deflection under a given load representing the actual wheel loads of vehicles. The deflection data can then be interpreted into useful information for rehabilitation and maintenance strategies at both the project and network levels [4].

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In the past, different pavement deflection devices have been used. Fundamental differences in deflection devices (such as the type of loading, loading speed, measurement and analysis technique) result in different recorded maximum deflections and deflection basin shapes. For over 40 years, thefalling weight deflectometer (FWD) has been the standard technology for evaluating the structural condition of pavements [5]. The FWD applies an impact load to the pavement and measures the maximum surface deflection through time histories of loading. However, due to its lower data collection efficiency and the requirement for lane closures during operation, the application of FWD is limited for network level inspection. Consequently, traffic speed deflectometer was introduced as a device capable of measuring vertical deflections under a continuously moving load using Doppler lasers at four or six points. Its ability to collect information at traffic speeds enables large spatial coverage and the creation of continuous deflection profiles, rather than measuring deflections at discrete points as the FWD does. However, the use of TSD is still limited; only a few countries operate this system in parallel with the FWD to correlate the deflections measured from both devices and gain a better understanding of the two measurement approaches [6].
The aim of this study is to compare the FWD and TSD surface deflections in order to understand differences in measurement outcomes and assess their suitability for pavement structural evaluation.

2 Description of falling weight deflectometer and traffic speed deflectometer methods

2.1 Falling weight deflectometer

The falling weight deflectometer (FWD), shown figure 1, is one of the most widely used non-destructive testing devices for evaluating pavement structural condition [7]. The development and advancement of the FWD in the form known today, originated at the Technical University of Denmark in 1976. Deflections of the pavement structure induced by the falling weight device generate a short duration impulse load, typically lasting between 30 and 40 milliseconds, closely simulating the loading effect produced by heavy trucks travelling at speeds between 50 and 70 km/h [8]. During testing, an impulse load is created by dropping a weight through a spring system onto a circular loading plate [9].

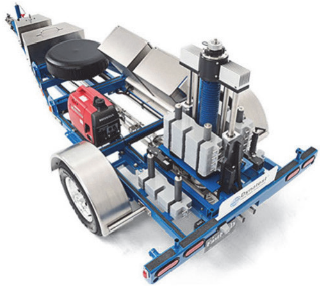

Figure 1 Falling Weight Deflectometer [10]

The pavement response to the applied impulse load is measured at the center of loading and at various radial distances using an array of sensors (geophones). The first sensor is positioned at the center of the loading plate, while the remaining sensors are placed at predefined intervals according to user requirements. The load is transmitted through a circular steel plate with a diameter of 300 mm for flexible pavements, whereas for rigid pavements the plate diameter is 450 mm. Changing the plate, diameter also alters the magnitude of the applied load.

For flexible pavement structures, the applied load is typically 50 kN, while for rigid pavements it is commonly 120 kN or higher. During testing, pavement temperature must also be recorded, as temperature significantly influences the mechanical behavior of asphalt layers. It is important to note that the shape and magnitude of the impulse load generated by the FWD are controlled by three parameters: the weight of the falling mass, the drop height and the number of rubber buffers attached to the mass. The function of the buffers is to decelerate the falling mass in order to control the load pulse shape. The impulse load varies in terms of load magnitude and pulse duration depending on the mass being dropped, the number of buffers used and the drop height applied during testing [11-13].

The main advantage of the falling weight deflectometer is its ability to provide information on the structural condition of all layers of both flexible and rigid pavement structures, including the subgrade. This means that, based on measured deflections, the elastic modulus of each pavement layer can be estimated using a procedure known as backcalculation. By determining the mechanical properties of the pavement layers, critical stresses and strains within the pavement structure can subsequently be calculated and used to assess the remaining service life of the pavement [14]. Furthermore, deflection measurements enable the identification of critical locations along the pavement as well as the evaluation of the severity of potential cracking in stabilized layers. In addition to the previously mentioned advantages, study [1] reports that FWD testing can be used to determine the required overlay thickness for extending pavement service life, as well as to evaluate the degree of bonding between pavement layers. However, there are some challenges regarding the utilization of the FWD. Firstly, it provides discrete measurements, commonly at 25 or 50 m intervals. As a result, weak spots between two consecutive drop sites might not be detected. Secondly, the lane must be closed to traffic when the FWD operates. This may cause problems related to traffic congestion and can also be dangerous for the operators. Thirdly, the dropping weight of the FWD does not seem to accurately simulate continuous traffic loads. And finally, the FWD is slow and not efficient for network-level applications [15]. While FWD remains a valuable tool for detailed structural evaluation, the falling weight deflectometer was introduced as a faster, continuous alternative.

2.2 Traffic speed deflectometer

The first traffic speed deflectometer was developed and patented in the early 2000s by Greenwood Engineering in Denmark, and since then, it has been operational worldwide [16]. Currently, 22 TSD units are in use globally, distributed across Australia, China, South Africa, Brazil, Denmark, Germany, Italy, Poland, Lithuania, the United Kingdom and the United States [5]. To date, the TSD has proven to be a valuable network assessment tool due to its high production rate and its ability to maintain measurement repeatability over a range of test speeds and road conditions [17].

The TSD, shown in figure 2 (left), consists of a three-axle articulated truck that applies a specified load (typically 100 kN) to the pavement surface through its rear axle. A servo-hydraulic measuring beam is mounted on the trailer, positioned between the dual wheels of the rear axle [5]. The load is applied to the pavement through the vehicle axles, where multiple Doppler laser sensors placed on the beam in front of and behind the rear axle continuously measure deflection velocity (figure 2, right). Initially, when the Doppler laser was installed at a nominal 2-degree angle, the vertical deflection speed of the road surface under the load was measured. The ratio between the horizontal speed of the pavement response and the vehicle velocity was found to depend directly on the sensor driving speed. To eliminate this dependency, the vertical deflection speed was divided by the instantaneous measured velocity, resulting in the deflection slope at a given sensor location.

Figure 2 Traffic Speed Deflectometer (left); Schematic (right) [18, 19]

Therefore, the primary approach to working with TSD data is to use deflection slopes directly. To calculate deflection values from these slopes, specific deflection algorithms can be applied [16]. These algorithms generally use mathematical integration of the deflection slope curve to calculate TSD deflections [20]. Until now, several methodologies have been proposed to date. The first is the area under the curve (AUTC) method, and the second is the Euler-Bernoulli beam (EB) method. The AUTC method integrates the fitted slope curve, while the EB method solves the Euler-Bernoulli beam model on a Winkler foundation. Compared to the EB method, the AUTC method is more flexible for fitting the slope curve but is more susceptible to the variability of TSD measurements [5]. In addition, deflections generated from TSD must be corrected to a specific reference temperature, as the deflections of the AC layer are sensitive to temperature changes. Furthermore, Greenwood Engineering employs a parametric modelling approach based on the finite element method combined with the Laplace transform to derive pavement deflections. Within this framework, a synthetic algorithm is developed, and the simulated results are validated using the ViscoRoute software. Subsequently, Gaussian and Stable distribution functions are applied to approximate the deflection slope curve. The main advantage of expressing the deflection slope through a mathematical formulation is the possibility of linking the model coefficients directly to pavement structural properties. Although establishing such a formulation can be complex, once defined, the elastic moduli of pavement layers can be determined directly from deflection slope data, eliminating the need for additional post-processing procedures. Methods for determining the pavement layers' moduli from TSD deflection measurements are mainly categorised into two groups. The first approach is based on converting TSD deflections to equivalent FWD deflections using a regression model. Traditional back-calculation software systems based on linear elastic theory can then be used to estimate pavement layers' moduli. The second method uses TSD deflection raw data (e.g. TSD deflection slopes) and an elastic or viscoelastic back-calculation procedure [20, 21].

2.3 Comparative analysis of FWD and TSD measurements

The most fundamental difference between FWD and TSD is the loading mechanism, which can lead to some appreciable differences in the measured deflection values obtained from these two devices [2]. Therefore, the comparison is not as straightforward as it may seem. An FWD applies a pulsed load through a rubber-based circular plate seated on the road surface. A TSD applies load via pneumatic tyres arranged in a dual-tyre axle group, travelling at a typical truck speed of around 70–80 km/h [17]. Considering that asphalt exhibits complex viscoelastic behaviour, which is also dependent on load frequency, it is clear that a direct comparison between an impulse load and a rolling wheel load can yield different results [22]. Rith and Saleh [4] conducted a study comparing the FWD and TSD loading behaviour on surface deflections. To estimate surface deflection under FWD and TSD loads, ABAQUS and the 3D-Move programme were used, respectively. The results showed that FWD loading cannot represent the full range of TSD dynamic loads induced by rolling speeds and surface roughness. Brezina et al. [23] also compared TSD and FWD deflection results measured on flexible pavement structures in Italy and Slovakia.

They found the same trend in deflection results on sections from Italy, but for the road section in Slovakia, the trends differed. The differences were likely due to limited positioning accuracy of the two devices.

It is already known that deflection data can be applied in pavement management through several main approaches. One involves the use of deflection basin indices, such as the surface curvature index (SCI300), to evaluate pavement condition and estimate its remaining service life. The SCI index represents the difference between deflections measured with load cells at the centre of the plate (D0) and 300 mm from the centre (D300): (D0–D300), which characterises the condition of bound layers [24]. Nielsen and Jensen [25] compared the deflection results generated by both TSD and HWD on two runways at Copenhagen airport. The SCI300 values measured with the TSD showed good agreement with earlier HWD measurements on the runway. However, they concluded that the thickness of the pavement structure layers previously used for HWD back-calculation did not represent the pavement structure well. For this reason, back-calculated elastic moduli based on HWD and TSD did not agree as well as the raw measurements.

3 Experimental testing

In spring 2025, FWD and TSD deflection measurements were performed on A1 Highway in Croatia, on section Vodice – Skradin, in the southeast direction. The total length of measured section was approximately 9 km. The first deflection measurements were conducted at the beginning of April, using the Dynatest 8012 Fast Falling Weight Deflectometer, owned by TPA company. During standard FWD measurement, the dropped weight and dropping height remain constant, but in practice, the load applied to the pavement depends on site conditions. The applied load is influenced by pavement stiffness, surface profile, and the properties of the FWD device. To ensure comparable deflection values, they have to be normalized to a standard load, in this case 50 kN [24]. This load was applied through a 300 mm diameter plate. Deflections were measured at the centre of the plate (radial distance 0) and with nine geophones located 20, 30, 45, 60, 90, 120, 150, 180, and 210 cm from the centre of the plate. The distance between measurement points was 100 m. The average surface temperature during measurements was around 15°C. Due to the temperature-dependent viscoelastic behaviour of asphalt layers, FWD deflection measurements were normalized to a reference temperature of 20°C, using the formula from the Polish catalogue [26] “Catalog of Reconstructions and Repairs of Flexible and Semi-Rigid Pavements, 2014”:

$$D_{(0\ (T=20)} = \mathrm{D}_0 \cdot f_t \cdot f_s \tag{1}$$

$$f_t = 1 + 0.02 \cdot (20 - T_{surf}) \tag{2}$$

where D_0 is central deflection standardized to a load of 50 kN, f_t is temperature coefficient (2), T_{surf} is pavement surface temperature and f_s is seasonality coefficient (depending on the measurement period, varying from 1.0 to 1.28). TSD deflection measurements on the same section were performed by Greenwood Engineering company from Denmark, at the end of May 2025. The 100 kN load was applied through the dual tires of the rear axle, and deflections were measured using 11 Doppler laser sensors. The average speed of the TSD device during measurements was 80 km/h, allowing pavement deflections to be evaluated continuously, at 10-metre intervals. As FWD measurements were conducted at 100 m intervals, TSD deflection data were grouped into 100 m sections, and the average deflection value was determined for each section. The geographical coordinates of individual TSD measurement points were then carefully reviewed and compared with the coordinates of the FWD measurement locations to identify points with the closest spatial alignment. These values were subsequently compared with FWD measurements performed at approximately 100 m spacing.

As the average surface temperature during TSD measurements was around 37°C, TSD deflection results were also normalized to 20°C using equations (1) and (2). The results are presented in figures 3 and 4.

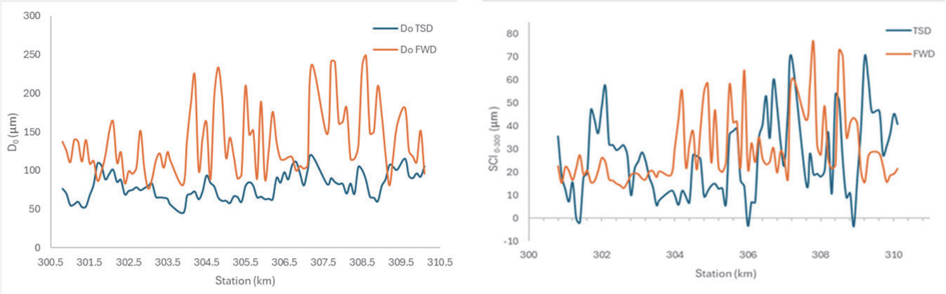

Figure 3 Comparison of FWD and TSD: central deflections (left); SCI (right)

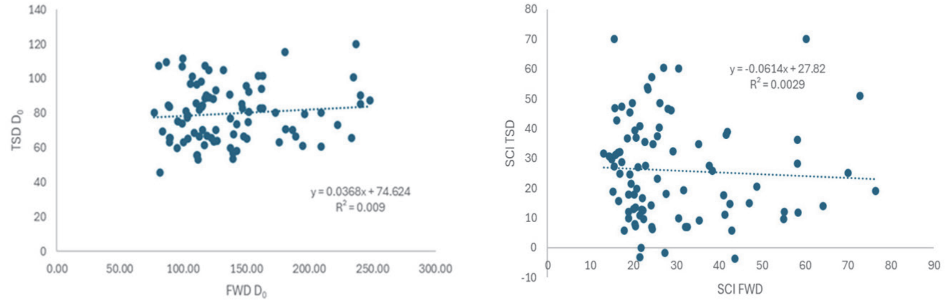

Figure 4 Regression analysis of FWD and TSD: central deflections (left); SCI (right)

The comparison of TSD and FWD measurements shows noticeable differences in both D_0 and SCI_{300} parameters along the analyzed section. Central deflection D_0 values obtained from FWD are much higher than those from TSD, which actually show lower amplitude and smoother spatial variations (figure 3, left). For the SCI_{300} parameter, TSD measurements exhibit higher variability and more pronounced oscillations compared to FWD results (figure 3, right). High SCI values from TSD are strongly correlated with the occurrence of surface cracks and degradation of the wearing course, underscoring the capability of the TSD method to detect shallow structural deficiencies. The extremely low R² values presented in figure 4 demonstrate that there is no statistically significant linear relationship between FWD and TSD deflection measurements. The absence of correlation can be attributed to several factors. Pavement surface roughness causes variations in tyre load magnitude due to dynamic excitation of the vehicle suspension system, which directly influences the measured deflection velocities and slopes in TSD measurements [27]. In addition, spatial sampling differs fundamentally. FWD provides discrete point measurements that may miss localized defects, while TSD continuously profiles the pavement, capturing short-term variations caused by surface texture and minor irregularities. This fundamental difference in sampling strategy contributes to the low correlation between the two methods. Furthermore, the viscoelastic nature of asphalt layers plays a crucial role. This asymmetry significantly alters the shape of the deflection basin, potentially rendering FWD-based methods invalid for processing TSD deflections, thereby affecting the reliability of graphical analyses and contributing to decreased correlation strength, as expressed by lower R² values [28]. The observed differences between results can also be attributed to variations in loading conditions. The continuous moving load applied during TSD testing produces an asymmetrical and time-dependent deflection response, while FWD measurements simulate a stationary impulsive load, resulting in more symmetrical deflection basins.

Consequently, the variability between the two datasets contributes to reduced correlation and suggests that direct comparison or substitution of TSD and FWD results requires additional calibration or transformation procedures.

4 Conclusion

The aim of this study was to investigate the relationship between falling weight deflectometer (FWD) and traffic speed deflectometer (TSD) deflection measurements. The results revealed notable differences between the measured parameters, particularly regarding deflection magnitude and spatial variability. Analysis showed that FWD measurements generally produced higher D_0 values, whereas TSD measurements exhibited greater variability in SCI_{300} values. The lack of consistent correspondence between the datasets resulted in reduced statistical correlation between the two methods, indicating that variability observed in FWD deflection measurements cannot be fully explained by TSD data. These variations are primarily attributed to differences in loading mechanisms and the viscoelastic behavior of asphalt layers, which influence the shape of deflection basins. Additionally, longitudinal roughness and surface cracking can significantly affect TSD measurements by inducing additional dynamic responses and localized stiffness heterogeneity, potentially leading to distortion of deflection signals. Despite these differences, both devices were found to be reliable tools for pavement structural evaluation. TSD is particularly effective for network-level assessments and identification of surface related distresses, whereas FWD enables detailed evaluation of structural performance and mechanical properties of individual pavement layers. Future research should focus on developing robust correlation models between these two measurement techniques and examining the influence of factors such as temperature, loading speed and pavement structure on measurement comparability.

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