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RESEARCH ARTICLE

Performance Evaluation of Traffic Speed Deflectometer Based on Virtual Standard Test Road

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ABSTRACT It is challenging to find actual standard test roads (ASTRs) to evaluate the measuring performance of the Traffic Speed Deflectometer (TSD), leading to misjudgment of its evaluation results. To address this issue, a method to construct virtual standard test roads (VSTRs) using in-service roads is proposed. Firstly, the principle of TSD based on the Laser-Doppler effect to measure pavement deflection is introduced, and the shortcomings of traditional evaluation methods are reviewed and summarized. Secondly, an adaptive construction method for VSTRs is proposed based on the K-means clustering algorithm. It layers the Falling Weight Deflectometer (FWD) measurements on in-service roads and reconstructs them as virtual roads with stable deflections but different ranges. Thirdly, two new indexes, the coefficient of variation CV_k and the influence coefficient of speed ICS_k, are proposed to replace the traditional indexes, such as repeatability and correlation coefficient. Finally, the feasibility of evaluating TSD performance based on VSTRs and the new indexes is verified by experiments. Results show that the newly constructed VSTRs solve the problem that the ASTRs are challenging to obtain, reducing the experimental requirements for evaluating TSD, and the new indexes achieve an efficient and scientific evaluation of TSD.

INDEX TERMS Traffic speed deflectometer (TSD), deflection, virtual standard test road (VSTR), adaptive construction, performance evaluation.

I. INTRODUCTION

Deflection is a significant property reflecting the bearing capacity of the pavement [1]. Earlier, instruments such as the Benkelman Beam Deflectometer (BBD) and the Falling Weight Deflectometer (FWD) were used to measure it. However, such instruments need to stop for 1-2 minutes during each test and suffer from poor safety and low efficiency [2], [3]. Currently, the focus of researchers has gradually shifted to high-speed, continuous, and non-destructive measurements [4], [5], [6]. The Traffic Speed Deflectometer (TSD) [7], [8] has recently received much attention in the road detection field due to the advantages of high detection efficiency and no need for road closure. This instrument is equipped with multiple Laser-Doppler vibrometers (LDVs) [9], [10] in front of the rear wheel load center of the trailer. It calculates the pavement deflection during high speed using Laser-Doppler technology, Euler Bernoulli beam theory, and the 2-parameter model of deflection basin or area method [8]. Its detection speed can reach 100 km/h, and the deflection output interval can be customized, such as 10 m, 100 m, and 1 km [11], which can better meet road network-level pavement deflection requirements than traditional instruments.

As a complex measuring instrument, factors from both internal and external sources may cause inaccurate TSD output, such as the deflection model [12], dynamic axle

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load [1], road roughness [1], [13], temperature [9], and road noise [14]. Therefore, it is essential to analyze the accuracy of the measured value and evaluate the measuring performance of TSD. Due to the lack of standard test roads that can provide stable and accurate deflections, currently, scholars at home and abroad mainly evaluate the performance of TSD based on the idea of comparisons [15], such as the repeatability and speed influence of its measured values, and correlation with other instruments.

Repeatability and speed influence analysis are used to evaluate the stability of the measurements of the same instrument. In contrast, correlation analysis is used to evaluate the consistency or accuracy of measurements from different instruments. Wix et al. [16] compared the TSD measurements in New South Wales in two years and found better repeatability of the maximum deflection. Liao et al. [1] showed that the variability of TSD measurements at three speeds (30, 50, and 80 km/h) was lower than 5%. Shrestha et al. [17] discussed the repeatability and correlation of TSD using approximately 9540 km of measuring data. Research by Li et al. [7] showed that the TSD had a high correlation with BBD measurements, satisfying the requirements of road network-level deflection measurement. Liao et al. [1] and Abohamer et al. [2] declared that the correlation coefficients of TSD and FWD measurements reached 0.945 and 0.972, respectively. Nielsen et al. [10] concluded that the FWD and TSD measurements, although similar, were not equivalent, and their details differed. Levenberg et al. [18] believed that the different loading mechanisms, load action time, pavement dynamic deformation mechanisms, and deflection calculation methods were the main reasons. In particular, the load of traditional instruments such as FWD is relatively constant when working, and its values are independent of speed, road roughness, and other factors. In contrast, the fluctuation amplitude of TSD is as high as 33% of that under the static load [2], [19]. Although the values may vary, there is a strong correlation between FWD and TSD measurements. For example, Manoharan et al. [20] even used a linear model to create the functional relationship between TSD and FWD measurements. In addition, some scholars have also built artificial neural network (ANN) models to train and predict the measured values from instruments with different measuring principles [2], [5], [21].

However, the existing performance evaluation methods and indexes have some shortcomings, leading to bias in the evaluation results. For example, only the measurements themselves are considered to analyze the repeatability and the speed influence, ignoring the deflections of the actual roads. Although the correlation analysis considers the measurements of two kinds of instruments simultaneously, a higher correlation coefficient may not necessarily indicate the accuracy of TSD due to the difference in the measuring principles [8]. In addition, some scholars have also tried to put forward other methods and indexes to evaluate TSD, such as deflection slope [14], surface curvature index (*SCI*) [18], [22], structural number of pavement (*SNP*) [20], [23], and base damage index (*BDI*) [24]. However, these new indexes derived from the deflection are also unable to evaluate the performance of TSD more comprehensively.

The shortcomings of the existing evaluation methods are mainly caused by the lack of ideal actual standard test roads (ASTRs). In theory, the deflection distribution of one or more ideal ASTRs along the driving direction should conform to specific rules, such as constant, gradually increasing or decreasing, changing with a certain function, and the deflections do not change significantly with time, temperature, humidity, rolling times, and other factors. But the ideal ASTRs are not easy to construct, maintain and obtain. All these current situations pose challenges to the efficient evaluation of TSD. Fortunately, many in-service roads have been used for comparative test analysis of TSD [2], [15], [25]. Therefore, the core of this research is to construct the ideal ASTRs through the actual in-service roads and propose scientific evaluation methods and indexes. However, the deflections and ranges of the actual roads are random, and it is not suitable to construct the ideal ASTRs directly based on one or more in-service roads. Considering that FWD has been widely accepted in road engineering [4], [5], it is relatively reasonable and feasible to extract some data from its measurements as a reference for standard test roads. The selected data can be spliced into new virtual roads. Thus, it is urgent to propose a data processing method that can adaptively layer FWD measurements according to the data characteristics and then reconstruct multiple ideal virtual standard test roads (VSTRs) with stable deflections.

When measuring in-service roads at 10 m or 50 m intervals using FWD and other conventional methods, the distribution of discrete deflections shows significant randomness and volatility. To construct ideal test roads with stable deflections, it is necessary to extract the deflections with similar values from these discrete data. The simplest method is to divide the deflections into equal intervals according to their amplitudes. However, this method may result in a division with null or too few elements due to randomness. Therefore, it is argued in this paper that these discrete deflections are, to some extent, characterized by aggregation and can be divided by clustering. Since the K-Means clustering method has been widely used in intelligent transportation [26], [27] and other fields and has shown excellent classification performance, the paper proposes classifying FWD deflection measurements based on it. Further, the classification results are spliced and reconstructed into multiple virtual roads with different deflection ranges, which solves the difficulty that the ASTRs are not easily obtained. Subsequently, for the newly constructed virtual roads, new performance evaluation methods and indexes such as the coefficient of variation $CV_{k,\mathrm{F}}$ and $CV_{k,\mathrm{T}}$ and the influence coefficient of speed ICS_k are proposed to improve the scientificity of evaluating TSD.

The rest of the paper is arranged as follows: Section II introduces the principles of pavement deflection of TSD measurement. In Section III, the existing common performance evaluation methods and indexes for TSD are listed, and their shortcomings are illustrated through experimental verification. Section IV proposes the improved TSD performance evaluation methods and indexes. Then, Section V confirms their scientificity and feasibility based on the same experimental data. The conclusions of the paper are presented in Section VI.

II. MEASURING PRINCIPLE OF ROAD DEFLECTION BASED ON LDV

As a non-contact, non-destructive, and high-speed dynamic measuring method, TSD conforms to the new trend of the times and has attracted the attention of many countries. Greenwood Engineering developed the prototype of TSD in the early to mid-2000s in Denmark [7], [8]. The basic structure of a TSD is illustrated in Fig. 1.

The core of the TSD is the measuring unit placed in front of the rear wheel, which consists of several LDVs arranged linearly on a stiff beam. The LDV measures the displacement or velocity of precision vibration using the Doppler effect [28], offering the advantages of fast dynamic response and non-contact. Specifically, the laser beam of the LDV is emitted to the object's surface to be measured, and the reflected laser beam generates a Doppler frequency due to the movement of the surface, thereby determining the vibration velocity of the measured point. For TSD, LDV is used to measure the deflection velocity V_d of point P in the deflection basin in real time under the rolling action of the rear axle wheel. The schematic diagram of the measuring principle is shown in Fig. 2.

Figure 3 shows the synthesis principle of the LDV for measuring the velocity V_m. The measured value V_m includes the component $V{\cdot}\sin(\beta)$ of the vehicle speed V due to non-vertical installation. The angle β between the LDV and the vertical direction is usually about 2 degrees. According to the angle relationship in the figure, the expression between V_{mi} of the i-th LDV, the vehicle speed V and the road deformation velocity V_{di} at the measuring point P_i is shown in (1), $i = 1, 2, \ldots, n$. Considering that β_i is small, the error introduced by replacing $V_{di}\cdot \cos(\beta_i)$ with V_{di} is less than 0.1% [29].

$$V_{mi} = V_{di} \cdot \cos(\beta_i) + V \cdot \sin(\beta_i) = V_{di} + V \cdot \sin(\beta_i) \quad (1)$$

where β_i represents the installation angle of the i-th LDV.

During each test, excitations from the engine and the road may cause unpredictable responses in the stiff beam, such as bumps, pitch, and cross-roll. To reduce this effect, TSD also installs sensors, such as gyroscopes, on the beam. In addition, considering that the n-th LDV is installed outside the deflection basin, it can be believed that the deflection velocity $V_{dn} = 0$ at the measuring point P_n. Then the deflection velocities V_{di} at the other measuring points P_i in the deflection basin can be obtained by (2), $i = 1, 2, 3, \ldots, n$.

$$V_{di} = V_{mi} - V_{mn} - V \cdot \sin(\beta_i - \beta_n) - G_x\pi \cdot (l_i - l_n)/180 \quad (2)$$

According to the Euler-Bernoulli beam theory, the 2-parameter models of the pavement deflection basin $y(x)$ and its slope $y'(x)$ are obtained respectively, and their expressions are expressed by (3).

$$\begin{cases} y'(x) = Ae^{-Bx}(\sin(Bx)) \\ y(x) = -\left(A/2B\right) e^{-Bx}(\cos(Bx) + \sin(Bx)) \end{cases} \quad (3)$$

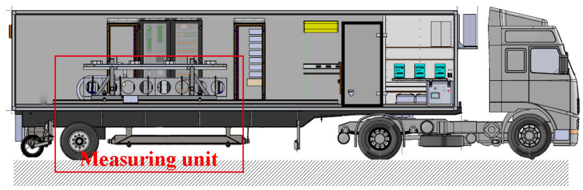

FIGURE 1. Schematic diagram of the basic structure of TSD [8].

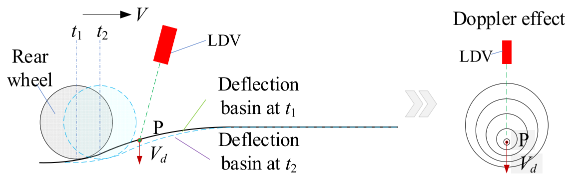

FIGURE 2. The measuring principle of pavement deflection velocity based on the Doppler effect.

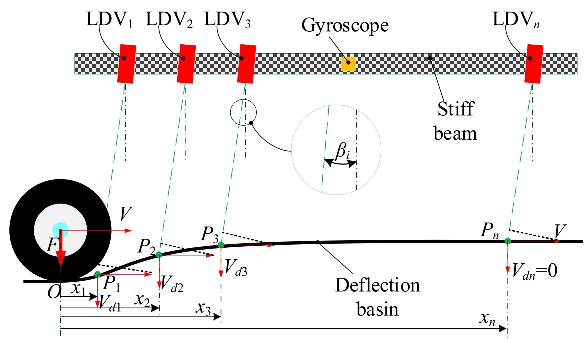

FIGURE 3. Simplified schematic diagram of the measuring unit and the velocity synthesis principle.

In the physical sense, the slope of the deflection basin curve $y'(x)$ is equal to the ratio of the deflection velocity $V_d(x)$ to the driving speed V, as shown in (4).

$$V_d(x) = V \cdot y'(x) \quad (4)$$

Therefore, in the practical application, TSD first measures the deflection velocity V_{di} at multiple positions x_i on the road ahead of the wheel through multiple LDVs fixed on the stiff beam [7], $i = 1, 2, 3, \ldots, n$. Then, the parameters A and B are obtained by fitting based on data processing methods such as the least squares method and equation (4). Finally, deflections of the measured pavement are calculated according to (5).

$$d_0 = y(0) = -A/2B \quad (5)$$

The above analysis shows that the deflection model of TSD is complex, and the correctness of its measurements and the measuring performance have been the focus of scholars at home and abroad. However, due to the lack of ASTRs, it is usually verified and evaluated on the in-service roads based on the comparison.

III. TRADITIONAL PERFORMANCE EVALUATION METHODS AND EXPERIMENTAL ANALYSIS FOR TSD

A. TRADITIONAL METHODS AND INDEXES

Currently, after obtaining the deflections of in-service roads, the following three methods are usually used to evaluate the measuring performance of TSD.

1) REPEATABILITY

Repeatability is used to evaluate the stability of the instrument values. The repeatability of m measurements of the TSD at the n-th measuring point is expressed as the standard deviation S_n, which is calculated by (6). A smaller S_n value indicates better TSD repeatability at the current measuring point.

$$S_n = \sqrt{\sum_{i=1}^{m} (x_i - \bar{x}_n)^2 / (m-1)} \tag{6}$$

where, x_i represents the result of multiple measurements at the n-th measuring point, and $\bar{x_n}$ denotes the mean value of x_i.

2) SPEED INFLUENCE

From (2) and (4), it can be seen that the deflections of TSD are affected by the driving speed V. This influence can be characterized by the influence coefficient of speed ICS. This index reflects the fluctuation of the measurements at the maximum and minimum speed V and is calculated as shown in (7). The parameter RD in this equation is the representative deflection of the measurements of TSD on the test road, and it can be computed according to (8). Based on the transportation industry standard of the People's Republic of China "JT/T 1170-2017 Traffic Speed Deflectometer", the measuring performance of a TSD is better when $ICS \leq 5\%$.

$$ICS = |RD_{V70} - RD_{V30}| / RD_{V70} \times 100\% \tag{7}$$

where, RD_{V70} and RD_{V30} represent the RD of TSD values at $V = 70$ km/h and $V = 30$ km/h, respectively.

$$RD = X + 1.65 \times \sigma \tag{8}$$

where, X and σ denote the mean and standard deviation of the deflections on the test road, respectively.

3) CORRELATION WITH FWD MEASUREMENTS

Due to the lack of ASTRs that provide true deflections, correlation analysis is used to illustrate the accuracy of TSD measurements and the measuring performance. Since FWD has been accepted by traffic and road industries at home and abroad, it is scientific and reasonable to use its measurements as the reference for pavement deflection. The correlation between TSD and FWD is expressed by the Pearson correlation coefficient COR, which is obtained by (9). Levenberg et al. [18] divided COR into five levels at an interval of 0.2 and concluded that the correlation between the two groups of data was "Strong" and "Very Strong" when COR ranged from 0.6 to 0.79 and 0.8 to 1.0.

$$COR = \sum_{n=1}^{N} \frac{(\bar{x}_n - X) \cdot (\bar{y}_n - Y)}{\sqrt{\sum_{n=1}^{N} (\bar{x}_n - X)^2 \cdot \sum_{n=1}^{N} (\bar{y}_n - Y)^2}} \tag{9}$$

where $\bar{x_n}$ and $\bar{y_n}$ denote the average values of FWD and TSD measurements at the n-th measuring points x_i and y_i, respectively, and X and Y represent the average values of $\bar{x_n}$ and $\bar{y_n}$ along the entire test roads, respectively.

B. EXPERIMENTAL ROAD AND INSTRUMENTS

The experimental test road is a long straight road in the traffic experimental field in Tongzhou District, Beijing, China, as shown in Fig. 4 (a). The total length of the test road is 1500 m, including a 300 m acceleration section, so the effective test road length is 1200 m. The experiment was scheduled to be carried out at night from 0:00 to 6:00 on September 18, 2021, with a temperature of 15 ° to 18 ° and a humidity of 70% RH to 80% RH. The initial starting point on the test road was recorded before the test to ensure consistent placement of the TSD output data. Paint markers were made at 10 m intervals to facilitate FWD measurements and data comparison.

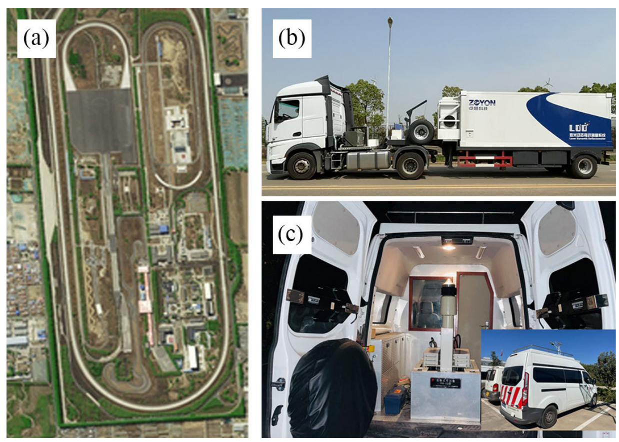

FIGURE 4. (a) The experimental test road, (b) TSD, (c) FWD.

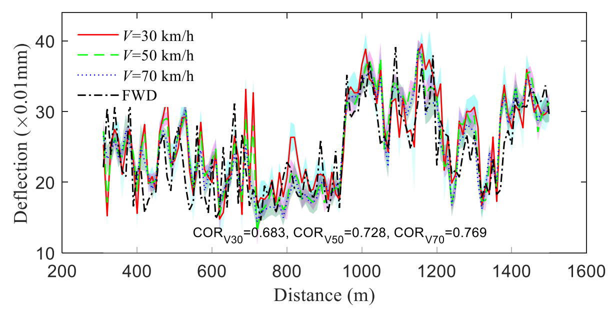

FIGURE 5. Measurements of FWD and TSD at 3 driving speeds.

One TSD manufactured by Wuhan Optics Valley Zoyon Science and Technology Co., Ltd, with the model number ZOYON-LDD, was selected as shown in Fig. 4 (b). The static load on the rear axle side of this instrument was 50 kN. Some of the main technical parameters and experimental results of this instrument can be found in studies by Liao et al. [1] and Li et al. [7]. The TSD was tested sequentially at 30 km/h, 50 km/h, and 70 km/h. The pavement deflections d_{TSD} corresponding to the paint marking points on the test road were output at 10 m intervals.

One FWD manufactured by Beijing Luxing Highway New Technology Co., Ltd. was selected for data comparison, as shown in Fig. 4 (c). The instrument model is FWD-150 with a peak load of 50 kN. During the test, the deflections were measured strictly according to the marked points on the pavement. This instrument also outputs 120 effective deflections d_{FWD} (excluding the starting point) on this 1200 m long effective test road.

Multiple measurements of TSD on the test road at three speeds are shown in Fig. 5. The center of the three curves in the figure is the average value of the multiple measurements, and the curve width is their standard deviation. In addition, the measured values of FWD, d_{FWD}, are also indicated by a dash-dot line in the figure. According to the trend of the four curves in Fig. 5, this TSD shows high measuring repeatability and stability and high similarity with FWD measurements. The performance of this TSD is analyzed below based on the traditional evaluation methods.

C. RESULTS BASED ON TRADITIONAL METHODS

1) REPEATABILITY ANALYSIS

Without loss of generality, the repeatability analysis is performed using the TSD measurements at $V = 50$ km/h. Five measurements m_i and their repeatability S_n of some points on the test road are listed in Table 1, $i = 1, 2, 3, 4, 5$, unit: 0.01 mm. The data in the table indicates that the maximum and minimum values of the S_n respectively reach 2.73×0.01 mm and 0.68×0.01 mm, indicating relatively high repeatability. In comparison, the unstable S_n may be because the five driving trajectories of the TSD are not entirely coincident.

TABLE 1. Measurements and their repeatability probabilities.

Distance(m)	m_1	m_2	m_3	m_4	m_5	S_n
310	25.97	27.85	27.17	26.15	24.90	1.14
410	21.63	23.66	24.55	24.00	26.24	1.66
510	26.25	26.27	27.69	28.49	27.34	0.96
610	24.05	24.66	24.94	26.22	27.47	1.37
710	26.81	29.21	23.09	27.87	28.62	2.42
810	19.34	25.24	24.18	19.64	20.53	2.73
910	23.08	18.41	19.64	15.58	18.41	2.71
1010	36.10	35.33	37.24	36.15	36.06	0.68
1110	34.34	31.53	32.85	33.52	32.56	1.05
1210	26.53	27.29	28.25	25.97	29.10	1.27
1310	23.06	24.92	24.29	23.20	22.16	1.09
1410	31.00	32.86	34.34	33.80	32.65	1.28

2) SPEED INFLUENCE ANALYSIS

According to (8), the representative deflections RD_{V30} and RD_{V70} at the speed of 30 km/h and 70 km/h are calculated as 34.92×0.01 mm and 33.77×0.01 mm, respectively. Further, the influence coefficient of speed ICS is 3.28% according to the equation (7), indicating that the measuring performance of this TSD is not significantly affected by the driving speed.

3) CORRELATION ANALYSIS WITH FWD

According to (9), the correlation coefficients COR of TSD and FWD measurements at speeds of 30 km/h, 50 km/h, and 70 km/h are 0.683, 0.728, and 0.769, respectively. Based on the research of Levenberg et al. [18], the TSD and FWD measurements showed a "Strong" correlation. In addition, when the driving speed V increases from 30 km/h to 70 km/h, COR increases by 12.6%, reflecting the trend of increasing COR with an increasing speed V. This is mainly because the asphalt pavement is viscoelastic. Its mechanical properties are related to the loading time of the rear wheel [30].

D. SHORTCOMINGS OF TRADITIONAL METHODS

According to the results of the above traditional performance evaluation methods and indexes, the measurements of TSD to be tested are trustworthy, and its measuring performance is relatively good. However, due to the lack of standard deflections, the traditional methods and indexes may misjudge the performance of the TSD.

According to (6) and (7), the repeatability analysis and speed influence analysis do not consider the actual deflections of the pavement, resulting in an inability to evaluate the TSD scientifically. For example, a TSD with erroneous output but stable results may also exhibit low repeatability S_n and low influence coefficient of speed ICS. As seen from (9), the correlation analysis considers the deflections from the other instrument. However, a single index value COR cannot fully reflect the measuring performance of TSD. From the measuring principles of FWD and TSD [8], they are reasonable in measuring different values on the same test roads. Therefore, the high or low values of COR are both possible. Conversely, a blindly higher COR may reduce the scientific validity of correlation analysis. Consequently, it is essential to find roads that provide standard or stable deflections.

Ideally, the shortcomings of the traditional methods can be compensated by constructing ASTRs. However, such roads have problems such as high construction costs and complex maintenance. In addition, asphalt is a non-standard material, and the pavement deflections provided are influenced by factors such as pavement temperature and humidity. All of these current conditions indicate that using ASTRs to evaluate the performance of TSD remains a significant challenge. In addition to utilizing ASTRs, a relatively ideal approach is to use multiple in-service roads with relatively stable deflections as standard test roads. However, this slightly worse experimental condition is also difficult to satisfy. In reality, the deflections and ranges on in-service roads are random and uncertain.

Therefore, finding multiple in-service roads with different ranges but stable deflections is still challenging.

Based on this, this paper proposes a method to construct the VSTRs. This method automatically classifies the FWD deflections of one or more in-service roads into multiple groups according to the data characteristics. It reconstructs them into numerous virtual roads with stable deflections but different ranges. Then, based on these virtual roads, new evaluation methods and indexes are underway to evaluate the TSD.

IV. IMPROVED EVALUATION METHOD FOR TSD

A. EVALUATION PROCESS

A new method for evaluating the performance of TSD is proposed in this section, and its primary process is shown in Fig. 6. The whole experiment and evaluation process consists of three main parts: (1) data acquisition, (2) data processing, and (3) data analysis.

In the data acquisition stage, two types of deflection measuring instruments, FWD and TSD, are used to obtain the deflections d_{FWD} and d_{TSD} on the same or more in-service roads and then form data pairs $C_{\mathrm{F,T}}$ according to the marked points on these roads. It's noted that there is no strict limit to the number and length of the selected in-service roads, only the full deflection range on all roads can cover the typical pavement, e.g. 10×0.01 mm to 40×0.01 mm, or other custom ranges. Since the pavement deflection is output at 10 m intervals, then both d_{FWD} and d_{TSD} are discrete data points. The characteristics of pavement data with strong spatial correlation on in-service roads are significantly suppressed.

In the data processing stage, the paper proposes a method to construct VSTRs based on the Adaptive Layering Method (ALM) to deal with pavement deflections. ALM can automatically divide the deflections d_{FWD} into different groups according to its data characteristics, thereby generating multiple deflection sets $d_{k,\mathrm{F}}$ with different ranges. Subsequently, the road segments represented by $d_{k,\mathrm{F}}$ are spliced and reconstructed into multiple VSTRs. Finally, according to the data pairing $C_{\mathrm{F,T}}$, the d_{TSD} is processed to obtain various deflection sets $d_{k,\mathrm{T}}$ of the TSD. The physical meaning of this result is expressed as follows: the standard deflection provided by a VSTR is $d_{k,\mathrm{F}}$, and the deflection value of virtual measurement by TSD on it is $d_{k,\mathrm{T}}$.

In the data analysis stage, the paper proposes to evaluate the measuring performance of TSD on each VSTR using new indexes such as $CV_{k,\mathrm{F}}$ and $CV_{k,\mathrm{T}}$, and ICS_k. The subscript k indicates the k-th VSTR, and F and T respectively denote the value provided by the VSTR and the value measured on it by TSD.

Compared to the traditional evaluation methods, such as repeatability, correlation, and speed variability, the newly proposed method mainly adds steps such as constructing VSTRs and proposing new performance indexes. However, these steps are carried out after obtaining the pavement deflections, which is software-level research work. Therefore, the new method does not significantly increase the effort required, nor does it cost more money or time.

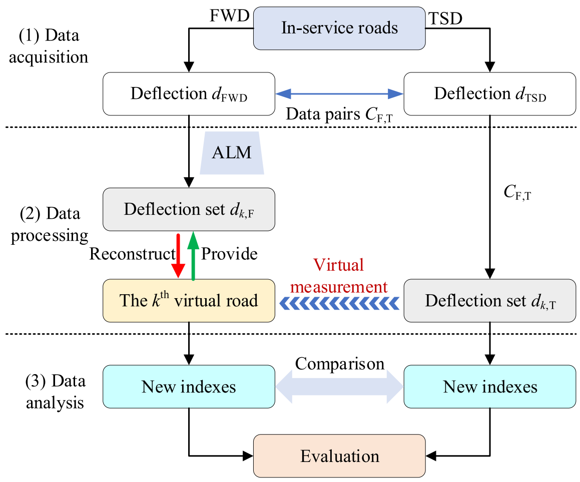

FIGURE 6. **The performance evaluation process of the TSD.**

B. ALM

ALM aims to cluster the deflections randomly distributed on the in-service roads adaptively. And its core algorithm is the k-means clustering algorithm. This algorithm divides a sample set containing N initial samples into K clusters without intersection, according to the distance between samples [31]. Its main characteristics are that the distance between samples in the same cluster is as small as possible, while the distance between samples in different clusters is as large as possible. The objective function of the paper in the classification process adopts the least square error of distance, as shown in (10).

$$E = \arg\min \sum_{k=1}^{K} \sum_{d_i \in c_k} \|d_i - \mu_k\|_2^2 \tag{10}$$

The schematic diagram of ALM dividing the in-service road and generating multiple VSTRs is shown in Fig. 7. The color difference of measuring points • in the figure indicates that the deflection of this point belongs to different ranges, and the difference in number means that the length of the subsequently reconstructed VSTR is different.

The process of ALM is illustrated by dividing the FWD measurements d_{FWD} into K clusters as an example. The main steps of the algorithm are as follows.

Step 1. Select K deflections d_i randomly from $d_{\mathrm{FWD}} = \{d_1, d_2, \ldots, d_N\}$ as the initial center (mean value) μ'_k of the cluster c_k.

Step 2. Calculate the Euclidean distance between d_i in d_{FWD} and μ'_k and assign d_i to the nearest cluster based on the distance to obtain K clusters $c'_k = \{d_{k,1}, d_{k,2}, \ldots, d_{k,j}\}$.

Step 3. Calculate the average value μ'_k of the deflection values in each cluster c'_k and update it as the new cluster center.

Step 4. Repeat steps 2 and 3 until the objective function (10) converges or reaches the maximum number of iterations M.

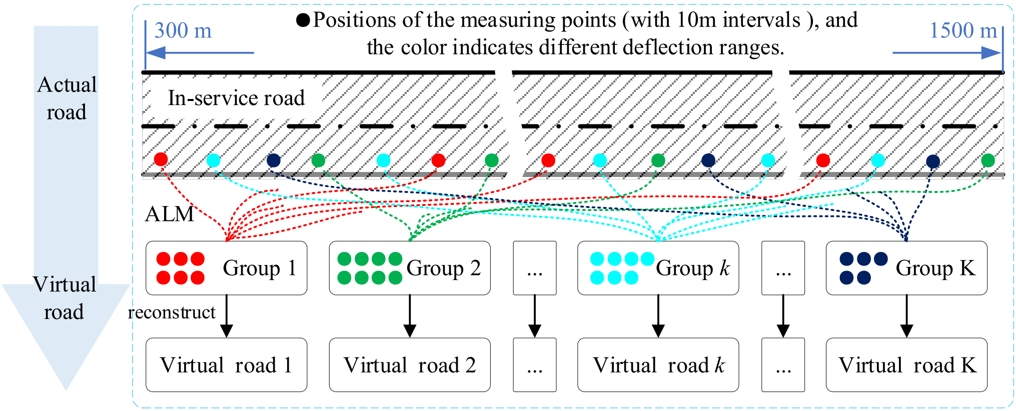

FIGURE 7. Schematic diagram of division process of in-service roads and construction process of virtual roads.

Step 5. Output the clustering results: cluster centers $\boldsymbol{U}' = \{\mu'_1, \ldots, \mu'_k, \ldots, \mu'_K\}$ and clusters $\boldsymbol{C}' = \{c'_1, \ldots, c'_k, \ldots, c'_K\}$.

Step 6. Calculate the coefficient of variation CV_k of the deflections in cluster c'_k. If $CV_k > 5\%$, then $K = K + 1$. Repeat Steps 1 to 5 until $CV_k \leq 5\%$ for all clusters.

Step 7. Arrange μ'_k in ascending order to get new cluster centers $\boldsymbol{U} = \{\mu_1, \ldots, \mu_k, \ldots, \mu_K\}$, and reorder the clusters c'_k in the same order to get new clusters $\boldsymbol{C} = \{c_1, \ldots, c_k, \ldots, c_K\}$.

Step 8. Output the final clustering results: value K, cluster centers $\boldsymbol{U}$ and clusters $\boldsymbol{C}$.

The elements in each cluster are the deflections with similar values, and μ_k is the average. K is the number of the final generated VSTRs.

C. IMPROVED EVALUATION INDEXES

After obtaining multiple virtual roads, two new indexes are proposed to compensate for the shortcomings of traditional indexes and methods.

1) COEFFICIENT OF VARIATION CV_K

The coefficient of variation CV_k reflects the degree of dispersion of each value on the unit mean. In this paper, this index is used to reflect not only the stability of the deflections provided by each VSTR but also the measuring performance of the TSD on it. The coefficient of variation of the deflections provided by the k-th VSTR is assumed to be $CV_{k,\mathrm{F}}$, and the coefficient of variation of the TSD measurements on it is $CV_{k,\mathrm{T}}$; see (11) for their calculation equations. Theoretically, the $CV_{\mathrm{k,F}}$ should be small enough, e.g., $CV_{\mathrm{k,F}} \leq 5\%$, while the $CV_{k,\mathrm{T}}$ of a well-performing TSD should be close to it.

$$CV_{k,i} = \sigma_{k,i}/\mu_{k,i}, \quad k = 1, 2, 3, \ldots, K \tag{11}$$

where, the subscript i denotes F and T, corresponding to FWD and TSD, respectively.

2) SPEED INFLUENCE COEFFICIENT ICS_K

According to (2) and (4), the TSD deflections, d_{TSD}, are influenced by the driving speed V. However, this effect is inconsistent with current research conclusions [8]. This may be related to the differences in the measuring performance of the TSD itself or the unstable deflections of the test roads used previously. After reconstructing multiple VSTRs with stable deflections, the influence of the speed V can be analyzed based on the speed influence coefficient ICS_k of the TSD measurements on these virtual roads. The equation for ICS_k is given in (12). In contrast to the traditional method of using a single index, ICS, to characterize the performance of TSD over the entire test road, this new index is a set of data that can mine the information implied in d_{TSD}. Although the new index ICS_k does not introduce the true deflections of the actual roads, the stable deflections of multiple virtual roads can be regarded as the virtual standard values. Since the deflection range of each virtual road is different, multiple ICS_k can comprehensively reflect the measuring performance of TSD. A well-performing TSD should keep the ICS_k low for all these virtual roads. Based on experience, the paper believes that a TSD has good measuring performance only when the index ICS_k corresponding to all virtual roads is less than or equal to 5%.

$$ICS_k = \frac{\left|RD_{k,\mathrm{T,V70}} - RD_{k,\mathrm{T,V30}}\right|}{RD_{k,\mathrm{T,V70}}} \times 100\% \tag{12}$$

where, $RD_{k,\mathrm{T,V30}}$ and $RD_{k,\mathrm{T,V70}}$ respectively represent the representative deflections when TSD drives at the speeds of $V = 30$ km/h and $V = 70$ km/h on the k-th VSTR.

In addition, considering that the modulus of viscoelastic pavements is influenced by the loading time [30], $RD_{k,\mathrm{T}}$ theoretically should not cross each other at the three speeds and have a good linear relationship with $RD_{k,\mathrm{F}}$. From this perspective, the measuring performance of TSD can also be qualitatively evaluated.

V. PERFORMANCE EVALUATION BASED ON NEW METHODS

A. CONSTRUCTION RESULTS OF VSTRs

The minimum and maximum values of the FWD deflections d_{FWD} on the test road shown in Fig. 4 (a) are 14.61×0.01 mm and 39.13×0.01 mm, respectively. The number K of VSTRs was empirically set to 10. Figure 8 shows the deflection distribution on these 10 virtual roads based on ALM, and colored points • represent them. Ten polylines with different colors connect the deflection points • belonging to the same cluster without crossing each other. Due to the relative randomness of the pavement deflections, the number of deflection points on each line is inconsistent, illustrating precisely the effectiveness and reasonableness of the ALM.

According to the division principle of the original in-service road in Fig. 7, each test point • in Fig. 8 represents the deflection of the road segment with a length of 10 m. Multiple road segments in the same polyline are spliced and reconstructed into one virtual road. Table 2 lists the deflection ranges on each road. The table shows that the length of the deflection range of each virtual road is about 2 × 0.01 mm, except for the 10th road with about 4 × 0.01 mm. The results show that the deflection of each virtual test road is relatively stable, and it is scientific and reasonable to take it as an ideal standard test road. The following is an analysis of it through the new index $CV_{k,\mathrm{F}}$.

The coefficients of variation $CV_{k,\mathrm{F}}$ of the deflections provided by these 10 virtual roads are shown in Fig. 9. The figure shows that the maximum and minimum values of $CV_{k,\mathrm{F}}$ are 4.24% and 1.97%, respectively, and the average value is 2.65%. Affected by the sorting step in ALM, the smaller and larger deflections on the in-service road are classified into the 1st and 10th virtual roads, respectively. This results in the indexes $CV_{1,\mathrm{F}}$ and $CV_{10,\mathrm{F}}$ corresponding to these two virtual roads reaching 4.24% and 4.22%, respectively. Except for these 2 virtual roads, the coefficients of variation $CV_{k,\mathrm{F}}$ for the remaining 8 roads are less than 3%. The above results show that the proposed ALM effectively divides the FWD data, and the proposed road reconstruction method generates virtual test roads with stable deflections. Therefore, it is reasonable to use these virtual roads as VSTRs and replace the ASTRs, which increases the scientificity of subsequent evaluation of TSD.

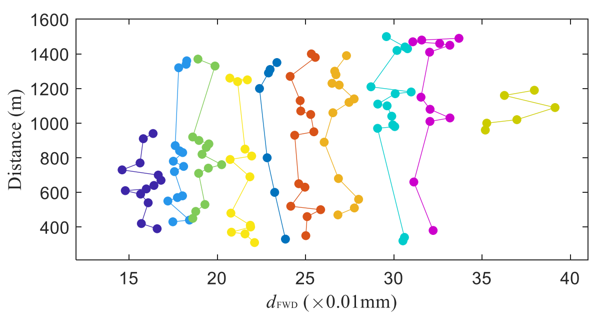

FIGURE 8. The deflection distribution of different virtual roads.

B. RESULTS BASED ON IMPROVED METHODS

The coefficients of variation $CV_{k,\mathrm{T}}$ of the TSD deflections on these 10 VSTRs at three speeds are shown in Fig. 9, $k = 1, 2, 3, \ldots, 10$. The figure shows that, except for the 10th VSTR, $CV_{k,\mathrm{T}}$ are all at levels greater than 10%, especially their maximum values reach 21.61%, 22.74%, and 22.37% at three speeds, respectively. Compared with the deflection variation coefficient of less than 5% provided by all VSTRs, such results indicate that the measuring performance of this TSD is not good.

TABLE 2. Deflection range of 10 virtual test roads (unit: 0.01mm).

Virtual road	Deflection range	Virtual road	Deflection range
1	14.61~16.81	6	24.13~25.85
2	17.20~18.42	7	26.05~28.00
3	18.61~20.25	8	28.70~30.98
4	20.71~22.11	9	31.07~33.69
5	22.39~23.86	10	35.18~39.13

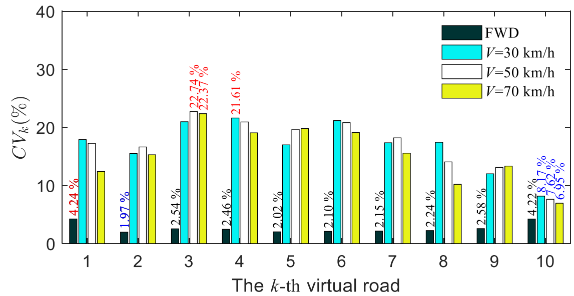

FIGURE 9. The variation coefficients $CV_{k,\mathrm{F}}$ and $CV_{k,\mathrm{T}}$ of deflections on these virtual roads, $k = 1, 2, \ldots, 10$.

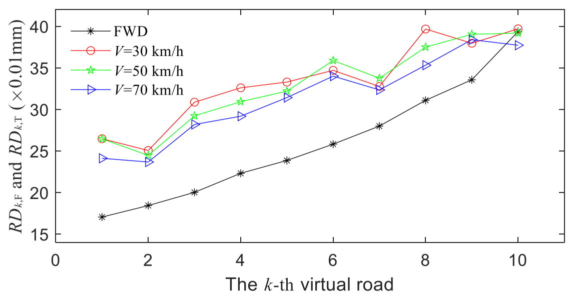

FIGURE 10. The representative deflections $RD_{k,\mathrm{F}}$ and $RD_{k,\mathrm{T}}$ on these virtual roads, $k = 1, 2, \ldots, 10$.

The representative deflections $RD_{k,\mathrm{F}}$ and $RD_{k,\mathrm{T}}$, provided by these 10 VSTRs and the measurements by TSD on them, are shown in Fig. 10, $k = 1, 2, \ldots, 10$. The figure shows that $RD_{k,\mathrm{F}}$ increases gradually, as expected, while $RD_{k,\mathrm{T}}$ does not strictly show a gradual increase trend, indicating that the measuring performance of this TSD needs to be improved. In addition, the figure shows that the magnitude relationship of $RD_{k,\mathrm{T}}$ under the three speeds is rough as follows: $RD_{k,\mathrm{T,V30}} > RD_{k,\mathrm{T,V50}} > RD_{k,\mathrm{T,V70}}$. This is related to the deflections of the asphalt pavement being affected by the moving speed of the load. However, this relationship is different on the 6th, 7th, and 9th virtual roads, which also reflects that the measuring performance of the TSD to be tested is not stable.

The speed influence coefficients ICS_k of the TSD measurements on these 10 VSTRs are shown in Fig. 11. The figure shows that index ICS_k has significant randomness, and its maximum value reaches 12.33%, indicating that the measuring performance of this TSD is greatly affected by the driving speed. In other words, this TSD fails to reduce the influence of speed on the deflection measurements to a

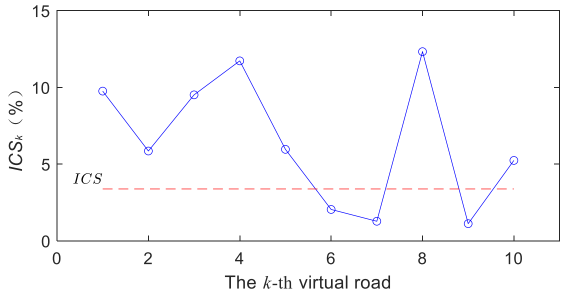

FIGURE 11. Speed influence coefficient ICS_k of TSD measurements on these VSTRs.

reasonable range. The index ICS_k corresponding to different virtual roads reflects the performance of TSD in different deflection ranges, thus allowing a more comprehensive evaluation of its performance. This is more convincing than the traditional method of utilizing the entire in-service road to obtain a single index of $ICS = 3.28\%$ to evaluate the TSD performance. From the above results, the implicit information of TSD measurements is excavated by the new index ICS_k.

VI. CONCLUSION

This paper proposes a method to construct the virtual standard test roads (VSTRs) using the existing in-service roads and presents new methods and indexes to evaluate the performance of TSD scientifically. The main conclusions of the paper are as follows:

(1) The adaptive layering method (ALM) of deflections, with K-means clustering as the core idea, is the premise of constructing VSTRs. This method can adaptively group deflections of in-service roads according to their numerical characteristics. It has no obvious restriction on the length, number, and deflection ranges of the original test roads, and reduces the experimental requirements for evaluating TSDs.

(2) The reconstructed multiple virtual roads are regarded as standard roads that can provide relatively stable deflections with different ranges. The measured values of TSD can be considered obtained by virtual measurements on these virtual roads. The coefficients of variation of the deflections, $CV_{k,\mathrm{F}}$, provided by all VSTRs are less than 5%, with a mean value of 2.65%. Which improves the scientific and reasonable evaluation of the TSD based on the FWD deflections and solves the practical problems, such as the actual standard test roads (ASTRs) are not easy to construct and obtain.

(3) The segmentation and reconstruction of one or more in-service roads, according to their deflection values, provides insight into the information implied in the TSD deflections. On these virtual roads, the coefficients of variation, $CV_{k,\mathrm{T}}$, are all greater than 10%, and the influence coefficients of speed ICS_k show volatility with a maximum value of 12.33%. These results indicate that the measuring performance of the TSD to be tested is not good, failing to reduce the effect of driving speed V to a reasonable range. Compared with traditional methods that only give a single value, such as repeatability probability S_n, speed influence coefficient ICS and correlation coefficient COR, the newly proposed methods and indexes can reflect the robustness of TSD measuring performance for different deflection ranges.

As new non-destructive technology for pavement deflection, TSD's complex measuring model limits the rapid promotion of this technology. Although the new method based on VSTRs proposed in this paper can effectively evaluate the measuring performance of TSD, these deflection data are based on FWD measurement. As common sense, FWD has a time-consuming deficiency in testing on the original in-service roads and is not an ideal data source. In the future, the research goal is to develop a deflection calibration device for efficient and rapid evaluation of TSD performance.

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