

**USE OF HIGH-SPEED DEFLECTION DEVICES IN NETWORK-LEVEL PMS
APPLICATIONS: ARE WE READY?**

by

Gonzalo R. Rada, Ph.D., P.E., Sr. Principal Engineer (Corresponding Author)
Beth A. Visintine, Ph.D., Technical Professional
AMEC Environment & Infrastructure, Inc.
12000 Indian Creek Court, Suite F
Beltsville, MD 20705-1242

Nazarian, S., Ph.D., P.E.
Professor, The University of Texas at El Paso
College of Engineering, Civil Engineering
500 West University Avenue, El Paso, Texas, USA 79968

Raj V. Siddharthan, Ph.D., P.E.
Professor of Civil Engineering
Dept. of Civil & Environmental Engrg.
University of Nevada, Reno
1664 N. Virginia St.
Reno, NV 89557

Nadarajah Sivaneswaran
Federal Highway Administration
Office of Infrastructure Research and Development, HRDI (20)
6300 Georgetown Pike, McLean, Virginia, 22101

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ABSTRACT

As highway agencies begin to consider structural adequacy as part of their routine pavement management activities by incorporating deflection testing, it is important to advance from falling weight deflectometers (FWDs) to a more viable alternative for network-level applications. The development of devices that measure pavement deflections at traffic speeds represents this viable alternative. The modern versions of the devices include the Greenwood Traffic Speed Deflectometer (TSD) and the Applied Research Associates, Inc. (ARA) Rolling Wheel Deflectometer (RWD), but are these devices ready for implementation? To answer this question, the Federal Highway Administration (FHWA) undertook a study whose objective was to establish a reliable measure of the structural condition of pavements as it deteriorates over time under traffic and environmental loading, based on deflection measurements taken at traffic speeds. As part of the study, a literature review was conducted and questionnaires were developed for and provided to device manufacturers, owners and users, which were then followed-up by interviews. Both devices were found to be viable, so a work plan was developed and implemented to evaluate them. The work plan included field-testing and analysis activities, but it purposely did not contemplate comparisons with Falling Weight deflectometers (FWDs). This paper presents the major findings, conclusions and recommendations from the project effort to date. The only remaining activity is the development of processes for incorporating pavement structural information within pavement management system (PMS) applications.

INTRODUCTION

Highway agencies spend billions of dollars each year on various transportation infrastructure assets to meet legislative, agency and public expectations. Pavements are a major component of those transportation assets and pavement rehabilitation is one of the most critical, costly and complex elements. This is especially true at present, since a large percentage of pavement networks are reaching the end of their serviceable life, and pavement rehabilitation has become even more daunting given the funding constraints faced by the agencies.

At the heart of rehabilitation decisions is the PMS, which provides condition indices or scores for each pavement segment in the system. Earlier generations of PMS were driven by ride quality and distress as a direct result of the American Association of State Highway Officials (AASHO) Road Test. With advances in technology, PMS started to use distress and longitudinal roughness (e.g., International Roughness Index or IRI), as key pavement performance indicators. Both are important indicators, but another indicator needed to make rational investment decisions is structural adequacy. A few SHAs are beginning to consider structural adequacy as part of their routine PMS activities by incorporating deflection testing.

There is presently a large array of equipment that can be used to measure deflections resulting from an applied load. The most commonly used device in this country since the 1980s has been the FWD, which represent the state-of-the-practice. However, because they are a stop-and-go operation, lane closures are required, which cause traffic disruptions and create a safety hazard. Their frequency of testing is also significantly less than a continuous operation, which affects operational costs. These shortcomings are especially important in terms of network-level PMS applications.

To overcome the FWD shortcomings, several organizations have developed devices that can continuously measure pavement deflections at posted traffic speeds (up to 50 – 60 mph). The modern versions of these devices include the Greenwood TSD and ARA RWD. Much work has been done over the past decade towards advancement of these devices, but are they ready for

immediate implementation in the structural evaluation of pavements for network level PMS applications? This question is at the heart of the study presented here, and whose stated objectives are to:

1. Evaluate the capability of traffic speed devices that measure deflection for pavement structural evaluation at the network level for use in PMS applications.
2. Develop analysis methodologies for enabling the use of the device(s) meeting the above objective, or develop recommendations to further develop promising device(s).

The ultimate goal of the project is to establish a reliable measure of structural condition as it deteriorates over time based on traffic speed pavement deflection technology.

To accomplish the project goal and objectives, a two-phase effort was undertaken. The first phase focused on the identification and evaluation of capable devices, which included a literature review as well as survey questionnaires and interviews of device manufacturers, owners and users – both the TSD and RWD were found to be viable devices. A work plan was developed to evaluate whether the devices met minimum specifications related to the structural evaluation of pavements, including accuracy and precision of the measurements; it purposely did not contemplate comparisons with FWDs. This work plan was implemented as part of the second phase, which included field-testing activities and analyses of the data to evaluate each device.

This paper presents the major findings and conclusions from the project effort to date. The only remaining activity is the development of analysis methodologies for incorporating pavement structural information within PMS applications.

LITERATURE REVIEW

The objectives of the literature review were to investigate and evaluate previous, on-going, and proposed research projects relating to available traffic speed pavement deflection devices that had the potential to meet the project objectives. Three of the references reviewed contained recent comprehensive literature reviews on the subject matter, so they are presented next.

Arora et al. (2006) summarized the state-of-the-art of continuous deflection devices at the time and study also investigated new methods for structural evaluation. Key findings included:

- Best return on investment is realized when measurements can be used to delineate pavement sections that are structurally marginal.
- A high-speed device with more than one deflection sensor is desirable for delineating structurally marginal pavement sections with greater confidence.
- Uncertainty in delineating structurally marginal pavements is related to precision and accuracy of measured deflections; the greater the uncertainty, the greater the risk.
- Effort is needed to quantify variability of measured deflections, beyond spatial variability, due to changes in subgrade soil properties and construction-related variability.

Rada and Nazarian (2011) completed a study entitled “The State-of-the-Technology of Moving Pavement Deflection Testing.” Major study conclusions included:

- Despite need for further improvements, the Greenwood TSD can be used for two of the pavement applications identified: (1) identification of pavement changes/anomalies for use at network and project level and (2) determination of overall pavement structural capacity indicators/indices at network level. With some modifications, the TSD and RWD can be used for multiple applications within the next five years.
- An area of concern with the ARA RWD and Greenwood TSD is the compromise between repeatability and loss of details with spatial averaging. The threshold values for the repeatability and spatial averaging should be defined in the future.

Flintsch et al. (2012) as part of the Second Strategic Highway Research Program (SHRP2) Project R06(F) evaluated continuous deflection devices to support pavement management decisions. That study identified TSD and RWD as capable of meeting the criteria for speed, load and data collection and being close to production mode. Field verification of the TSD showed that it could be used for network-level data collection with adequate repeatability. The study recommended several improvements to the devices.

As a result of the literature reviewed, it was concluded the RWD and TSD are potentially viable devices, which merited further evaluation. To augment the literature review findings, questionnaires were developed for and sent to the device manufacturers as well as owners and users of the devices. Interviews were also conducted to follow-up with specific questions or to pursue clarification.

FIELD EVALUATION OF DEVICES

The main purpose of the field evaluation was to establish the precision and accuracy of the devices under consideration. Information collected device data, embedded sensor data, and environmental data. The MnROAD facility near Albertville, Minnesota was selected as the primary site since it provided a multitude of test sections in one location. The facility consists of a 3.5-mile (5.6-km) Mainline comprised of 45 cells and a 2.5-mile (4.0-km) closed-loop Low Volume Road comprised of 28 cells.

The MnROAD cells are instrumented with different types of sensors such as strain gauges and pressure cells. In addition to these sensors and as part of the study, four geophones and one accelerometer were installed as embedded sensors to measure deflection velocity and displacement parameters at three MnROAD cells. Geophones were used because they are inexpensive, can be easily ruggedized in steel casing, and their one-to-one correspondence to the TSD measured parameters. Accelerometers were used to verify the responses of the retrofitted geophones. Aluminum holders were machined to provide them the protection needed to withstand the testing process. The geophones were calibrated using a shaker table and a high precision, reference accelerometer to establish their frequency responses after they were placed in the metallic holders.

The performance of the sensors was verified using a FWD – one FWD sensor was placed directly on top of one of the embedded sensors. The FWD deflections were then compared with those reported by the embedded geophones and accelerometers. The sensor locations as well as the results from the comparison are presented in Figure 1. The deflections from the two systems were quite similar.

The data acquisition (DAQ) system used with the geophones and accelerometers consisted of a National Instruments USB-6211 and a laptop. During data collection, the only setting that needed to be modified was the speed of the vehicle before each test. This variable determined the amount of time needed to collect data with the DAQ system. MnROAD staff provided an Arbiter Systems GPS clock to ensure collected data were time-stamped. To properly trigger the sensors, infrared light-emitting diode (LED) positioning sensors were installed at each cell.

In addition to the MnROAD facility, an 18-mile (29.0-km) loop in Minnesota's Wright County was tested. The loop was separated into nine sections based on pavement structure and MnDOT provided the data for those sections. In addition to providing real life sections, the loop also contained tight turns and rolling hills that provided data to evaluate the effects of horizontal and vertical curves.

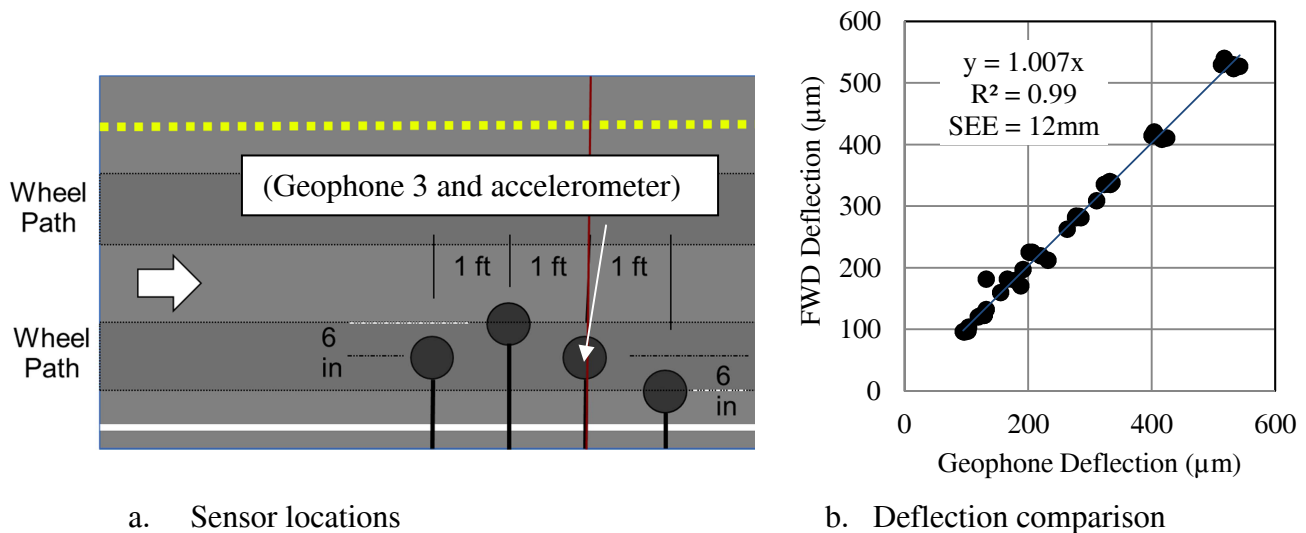


Figure 1. Evaluation of performance of embedded sensors with FWD

PERFORMANCE EVALUATION OF DEVICES

Accuracy

Three MnROAD cells (3, 19, and 34) were instrumented for the accuracy analysis. Accuracy was established by statistically comparing the results measured with the embedded sensors and those reported by the devices. The devices reported their averaged data at 33ft (10 m; TSD) to 50 ft (15 m; RWD) intervals, so the averaged data point closest to the embedded sensors was used in the accuracy study. As an example, Figure 2 compares the TSD and the RWD discrete measured values with the corresponding time histories from the embedded sensors. As shown in Figure 1, sensors were offset to maximize possibility of driving devices on top of an embedded sensor. Geophone 3 (GEO3) was used for comparison.

ARA RWD Accuracy

Table 1 contains the overall accuracy results for the RWD at the three MnROAD cells and at different speeds. The “Constant” column can be used to determine if there is a device related systematic uncertainty in measurements – since values change with cell and vehicle speed, the uncertainties in measurements cannot be considered systematic. The slopes of the best-fit line vary from 0.59 to 1.22 indicating moderate to significant deviation from unity, which is desired from a perfect device. The R^2 value should ideally also be close to unity. That is the case for Cells 19 and 34, but not for Cell 3 (stiffest pavement). The standard error of estimate (SEE) is 1.56 mils (0.04 mm) or less for Cells 19 and 34 and 1.95 mils (0.05 mm) and greater for Cell 3. Inaccuracy for Cell 3 varies from 8 to 42%, while for Cell 19 and 34 the maximum inaccuracies are 9% and 17%, respectively. The SEE, in conjunction with deflection range, is important in assessing minimum level of deflection changes or damage that the device can delineate.

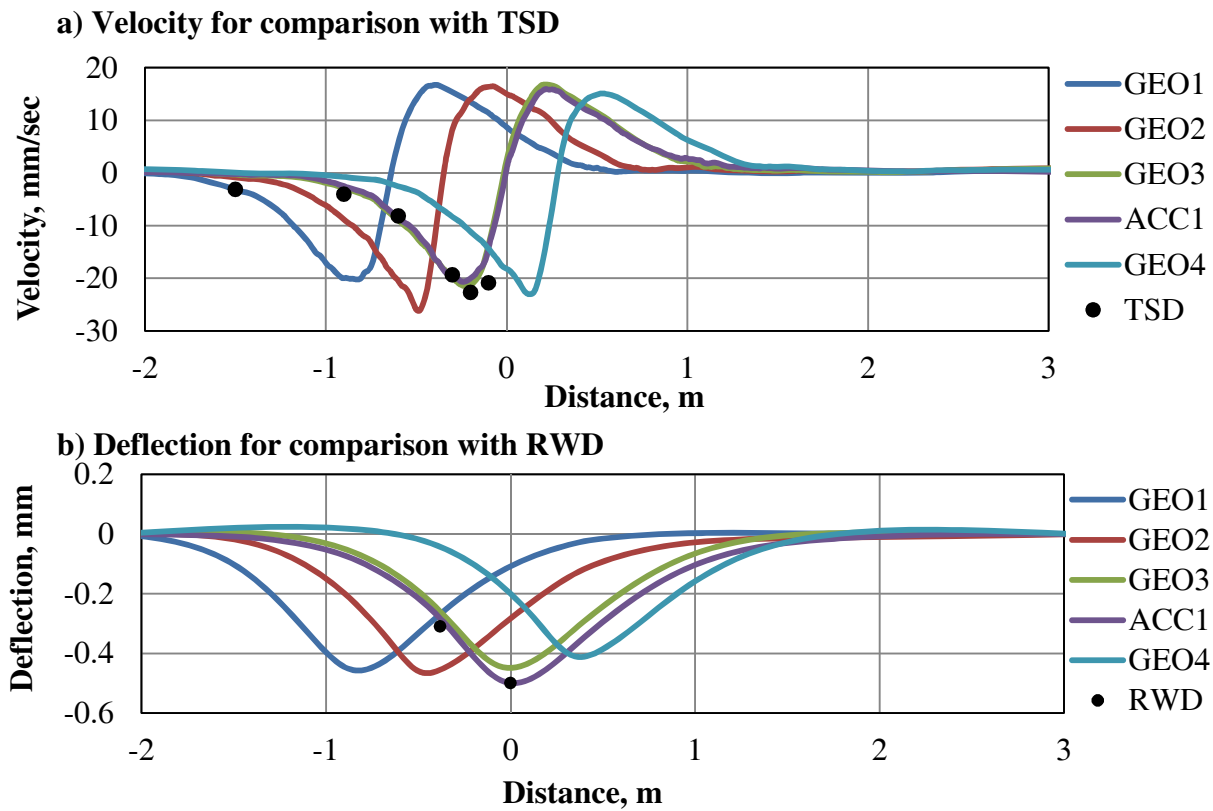


Figure 2. Comparison between embedded sensor deflections and device measurement

TABLE 1. OVERALL RWD ACCURACY STATISTICS

| Cell | Speed, mph (kph) | Overall Statistics | | | | |
|------|---------------------|--------------------|-------|----------------------|---------|------------|
| | | Constant | Slope | R ² Value | SEE, mm | Inaccuracy |
| 3 | 29.8 (48) | 0.02 | 1.22 | 0.71 | 0.05 | 32% |
| 3 | 44.7 (72) | 0.07 | 1.06 | 0.68 | 0.06 | 42% |
| 3 | 59.6 (96) | -0.06 | 1.22 | 0.80 | 0.05 | 8% |
| 19 | 29.8 (48) | 0.11 | 0.70 | 0.96 | 0.02 | 1% |
| 19 | 44.7 (72) | 0.19 | 0.59 | 0.90 | 0.04 | 7% |
| 19 | 59.6 (96) | 0.16 | 0.67 | 0.90 | 0.03 | 9% |
| 34 | 29.8 (48) | 0.16 | 0.84 | 0.99 | 0.02 | 17% |
| 34 | 44.7 (72) | 0.13 | 0.87 | 0.98 | 0.02 | 15% |

Another way of assessing accuracy is by calculating error associated with each sensor. It was determined that average errors from the replicate tests at each cell and speed varied between 12% and 41%. The median errors for the two RWD sensors were 26% and 27%. Figure 3 shows a plot obtained from the analysis of the RWD. Overall, the RWD deflections are 12% greater than the embedded sensors. With an R² value of 0.82 and an SEE of 2 mils (0.05 mm), the RWD may be more appropriate for less stiff pavement structures (deflections in excess of at least 8 mils [0.2 mm]). The errors were mostly distributed between 10% and 50%, with an average error of 27%, and an error of about 40% for a degree of confidence of 80%. This error does not vary much or in a systematic manner with speed. However, pavement stiffness appears to impact the RWD accuracy, but an obvious trend could not be observed.

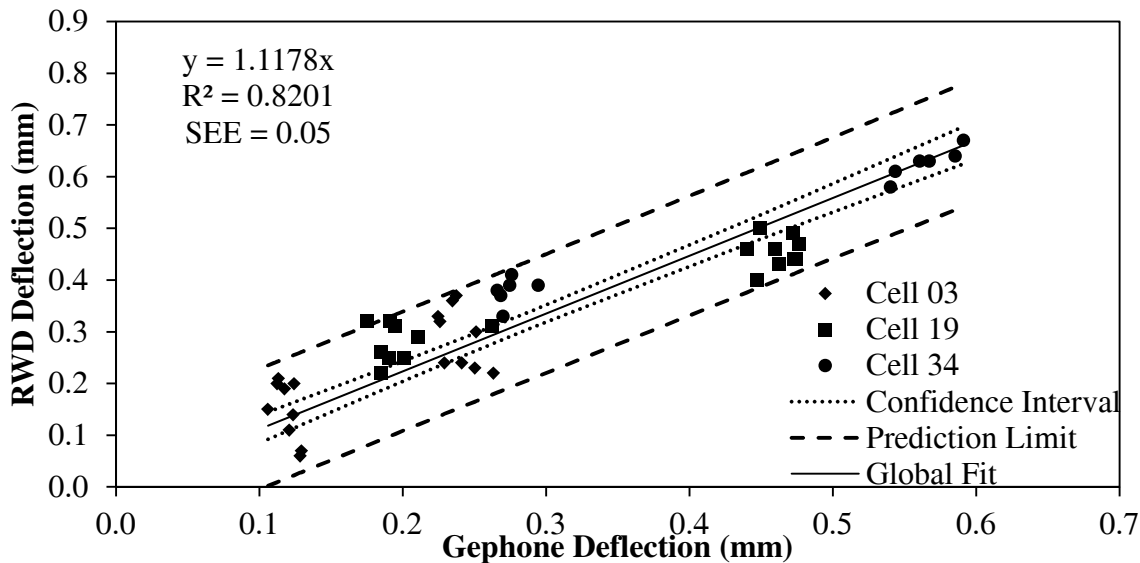


FIGURE 3. Overall comparison of deflections measured with RWD and embedded sensors

Greenwood TSD Accuracy

A similar procedure as for the RWD was followed for the TSD accuracy analysis. Table 2 summarizes the overall accuracy results from all cells and speeds. The slopes of the best-fit lines fall closer to unity except for the slowest speed in Cell 3. Most R^2 values are reasonably close to unity except for Cell 3 (stiffest pavement). The SEE vary between 0.003 ft/sec (0.96 mm/sec) and 0.0125 ft/sec (3.86 mm/sec), and they seem to increase as pavement becomes less stiff. Inaccuracy for all tests appeared small with the highest value being 15%. This time the stiffest section had the best average (less than 4%). The overall TSD accuracy results are also presented in Figure 4. The slope of the global fit depicts a difference of less than 8% with respect to the embedded sensors. This and an R^2 of 0.95 demonstrate the overall level of TSD accuracy. Most data points fall close to the global fit, generating a tighter confidence interval and prediction limit.

For the TSD more than half of the errors were found to be below 20%. Sensor accuracy was also evaluated with varying vehicle speeds. In most cases, the average error decreased or remained constant with an increase in vehicle speed. Also, the stiffest pavement (Cell 3) had the highest average error, ranging from 24% to 31%, at two different speeds. Cells 19 and 34 exhibited similar average errors (around 16% to 18%).

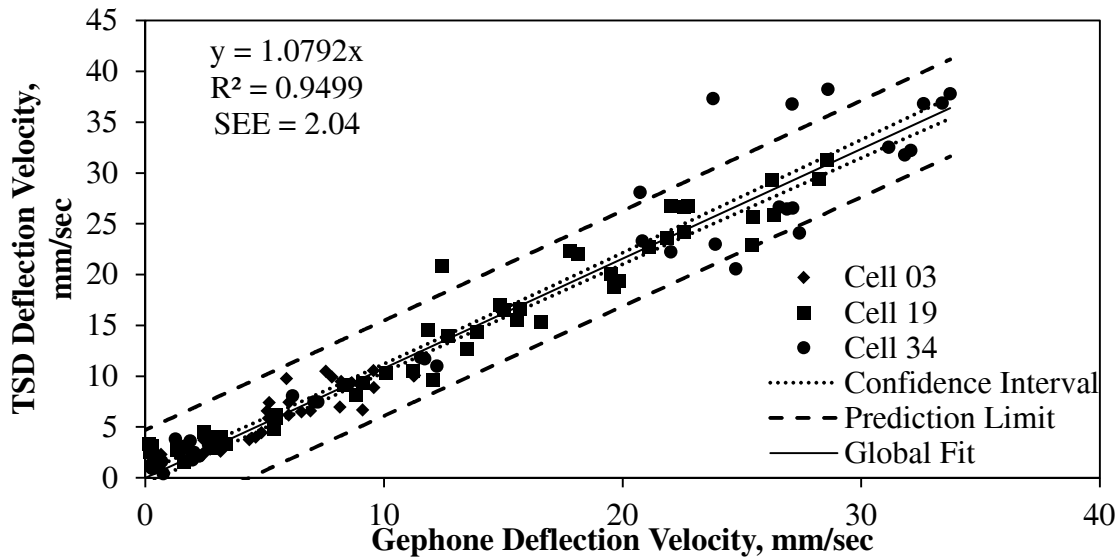
Precision

The evaluation of precision was carried out by analyzing the results obtained for most MnROAD cells and the Wright County loop. To better evaluate precision, the devices were tested at different speeds and at different times of the day. Data were collected up to five times (i.e., repetitions), at every cell and at two different speeds. Due to safety concerns, the MnROAD Low Volume Road tests were carried out at 30 and 45 mph (48 and 72 kph). These combinations resulted in a total of 78 precision passes.

The precision analysis started by developing color-coded Google maps. The average and coefficient of variation (COV) of the deflection parameters for each sensor from replicate passes were calculated for each reported test point and these values were color-coded. This color codification was also applied to vehicle speed and pavement surface temperature since these parameters can influence device precision.

TABLE 2. OVERALL TSD ACCURACY STATISTICS

| Cell | Speed, mph (kph) | Overall Statistics | | | | |
|------|---------------------|--------------------|-------|----------------------|---------|------------|
| | | Constant | Slope | R ² Value | SEE, mm | Inaccuracy |
| 3 | 29.8 (48) | 1.42 | 0.76 | 0.83 | 0.96 | 1% |
| 3 | 44.7 (72) | 1.25 | 0.91 | 0.85 | 1.42 | 7% |
| 19 | 59.6 (96) | 1.28 | 0.95 | 0.97 | 1.14 | 5% |
| 19 | 29.8 (48) | 2.08 | 0.98 | 0.93 | 2.29 | 10% |
| 19 | 44.7 (72) | 1.18 | 1.01 | 0.96 | 2.26 | 6% |
| 34 | 29.8 (48) | 0.93 | 0.96 | 0.96 | 2.37 | 1% |
| 34 | 44.7 (72) | 0.90 | 1.11 | 0.95 | 3.86 | 15% |

**FIGURE 4. Overall comparison of deflection velocities measured with TSD and embedded sensors**

After properly aligning the starting point of each pass using GPS coordinates provided by the devices, the next step entailed comparing the deflection parameters from the replicate passes at similar speeds. The raw data from different passes were first plotted and visually inspected to confirm the proper alignment of data. Statistical analyses were then carried out between each two individual pairs of data collected. Statistical parameters such as the R^2 value, the slope of the best-fit line, and the SEE were estimated for each pair and a student t-test analysis was carried out to determine whether each pair of data belonged to the same population. To summarize the extracted data in a manageable form, the minimum, maximum and median values of each of these statistical parameters were extracted. These results were then presented as box plots. Typical box plots that are presented in Figure 5 demonstrates the range, 25 and 75 percentiles and the median for the slope, R^2 , SEE and the range of measured values for the TSD.

Histograms of the distributions of the reported parameters were also plotted to visually evaluate the distributions of the data. Since the RWD data files included the standard deviations of the deflection parameters corresponding to the average values reported, the distributions of the COV were also calculated and demonstrated as well. Such analyses were performed on every sensor (6 sensors for TSD and 2 for RWD) of each device. To further evaluate precision, the

different passes were grouped together by time of the day (AM or PM), by speed (30, 45 or 60 mph [48, 72 or 96 kph]) and by pavement structure.

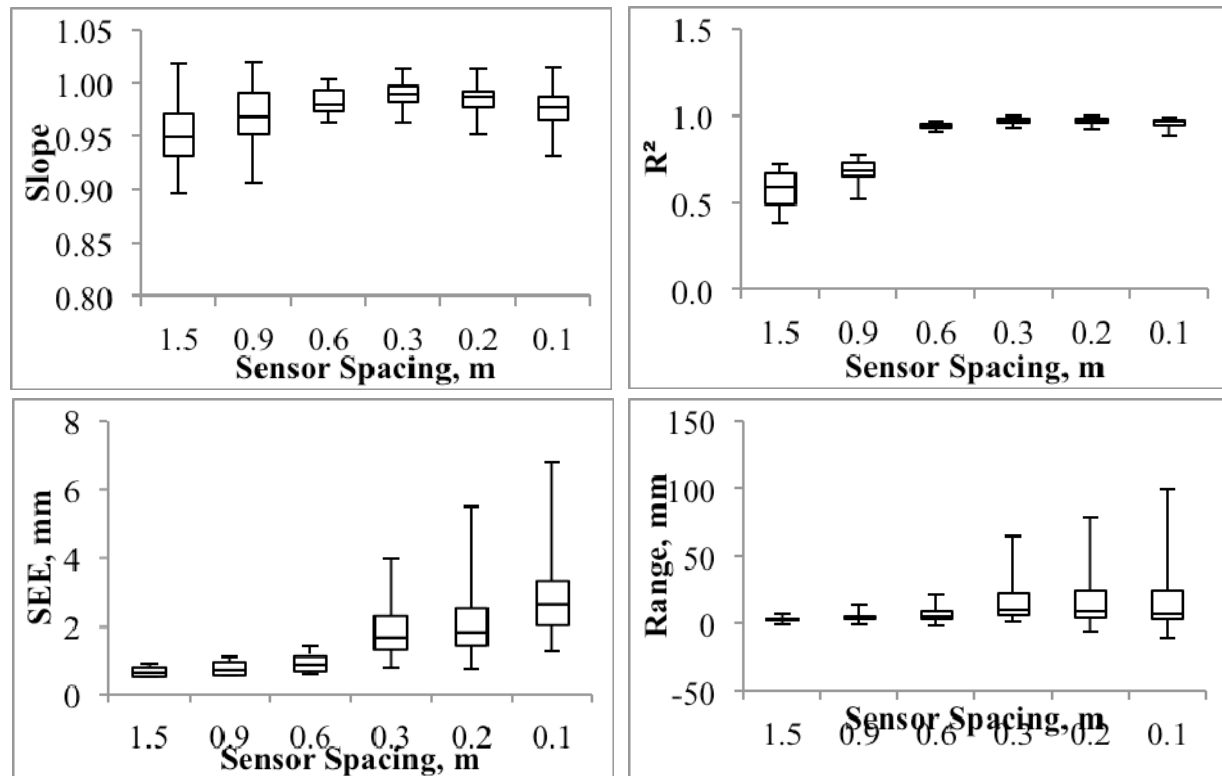


FIGURE 5. Typical box plots for precision analysis

ARA RWD Precision

With slopes between deflections from different passes averaging above 95%, both RWD sensors exhibited satisfactory performance in terms of overall reproducibility. However, the median R^2 values of 0.8 and less point to high scatter among deflections collected at each test point amongst different runs. The sensor located between the wheels exhibited higher R^2 values, especially along the Mainline.

The median SEE from relating the deflections from different passes were 4 mils (0.1 mm) or less. The uncertainty of the measurements can be evaluated by comparing the SEE with the range of deflections measured along the test sections. The median deflections were 23 mils (0.6 mm) or less for the sensor between the wheels and 16 mils (0.4 mm) or less for the sensor located at 1.25 ft (0.38 m) distance. As such, the median SEE is about 15% to 25% of the median deflections measured by sensors. These results indicate that in terms of precision, the RWD can perform more favorably on the pavement structures that yield deflection greater than 8 to 12 mils (0.2 to 0.3 mm).

The Wright County loop precision results showed that the RWD performs quite well under a realistic environment. The slopes of the relationships among different passes were typically 0.95 or better, which are close to the ideal value of unity. The R^2 values were also above 0.86 for both sensors. The median SEE values were about 10% of the median deflections for the sensor in between the wheels and about 15% for the sensor located 1.25 ft (0.38 m) from the load. It should be noted, however, that the data provided for the loop was averaged over 525

ft (160 m), whereas the data provided for the accuracy analysis was averaged over 49.250 ft (15 m) intervals. This may explain the better performance of the RWD along the loop.

Greenwood TSD Precision

For the TSD, the sensor precision varied with spacing. The median of the best-fit slopes for all sensors was greater than 95%, indicating that the replicate data are in good general agreement. The R^2 values of the relationships between different passes were in excess of 0.9 for the first three sensors, indicating high certainty in the repeatability of the results from different passes. The two farthest sensors yielded median R^2 values of less than 0.7 for the MnROAD Low Volume Road and less than 0.2 for the MnROAD Mainline. Clearly, a study to assess the sources of the uncertainties of the last three sensors is warranted. The SEE values varied between 0.003 ft/sec (1 mm/sec; for sensors farther from the load) and 0.01 ft/sec (3 mm/sec; for sensors closer to the load). Given the median deflection velocities varying by about 0.055 ft/sec (17 mm/sec; for the closest sensor) to about 0.0033 ft/sec (1 mm/sec; for the farthest sensor), the repeatability of the farthest three sensors may be of concern.

The precision analysis of the Wright County loop was done using data averaged at 33 ft (10 m) intervals. The performance of the TSD along the loop is similar or slightly worse in comparison to the MnROAD sections. The slopes of the best fit lines between repeat passes were greater than 0.92, but the R^2 values were less than 0.8. The SEE once again gradually decreased from 0.01 to 0.003 ft/sec (3 to 1 mm/sec), while the median range decreased from about 0.030 to 0.003 ft/sec (10 to 1 mm/sec). Again, the precision of the farther sensors is of concern.

PMS ANALYSIS METHODOLOGIES AND PROCESSES

As stated in the introduction, the only remaining activity in this study is the development of methodologies for incorporating pavement structural information within PMS applications. Towards development of these methodologies, the 3-D Move software (Siddharthan et al., 2002) is being used to identify promising indices/parameters and/or to develop new ones. This software is well suited to evaluate pavement responses measured with devices such as the TSD and RWD. The responses are estimated using a continuum-based finite-layer approach, which can account for factors such as load stress distributions, speed, and viscoelastic nature of some pavement layers. Each layer is treated as a continuum and the software uses the Fourier transform technique to handle loadings.

More specifically, the 3D-Move software will be used to answer questions such as:

- What is the sensitivity of measured deflection to vehicle speed and changes in material properties?
- Are there pavement response parameters – e.g., velocity, acceleration, shear strain, and elastic energy input – that are sensitive to pavement condition?

The 3D-Move software has been calibrated based on the device and sensor data collected at the MnROAD facility. Figure 6, for example, shows the comparison of displacements computed from 3D-Move to those measured by the embedded sensors at MnROAD. A good match between computed and measured displacements is shown.

SUMMARY AND CONCLUSIONS

This paper summarized the efforts and findings to date from a study aimed at determining the capability of traffic speed deflection measurement devices for evaluating pavement structural condition at the network level for use in PMS applications.

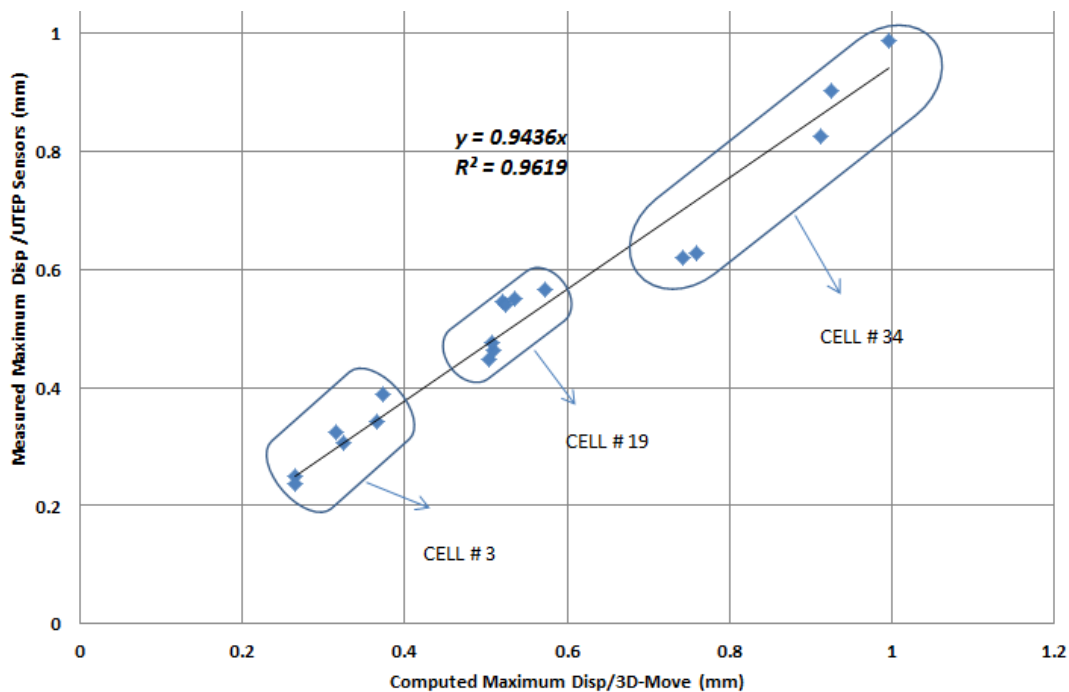


FIGURE 6. 3D-Move Maximum Displacements: 3D-Move versus Embedded Sensors

Towards achieving the study objectives, a literature review was undertaken to identify devices that have the potential to meet the stated objectives. To supplement the literature review, questionnaires were sent to device manufacturers, owners and users, and interviews were conducted to follow-up with specific questions. Based on these efforts, it was concluded that both the RWD and the TSD are potentially viable devices, which merited further evaluation.

Consequently, a field evaluation and data analysis work plan was developed and executed. Most of the field evaluation took place at the MnROAD facility, but testing was also conducted in a loop in Wright County, Minnesota. Prior to testing, geophones and accelerometers were embedded at selected cells, so the information available included device data, sensor data (existing MnROAD sensors and installed geophones and accelerometers), and supporting data. Based on analyses of these data, generally positive findings and conclusions concerning the accuracy and precision of the devices were developed. Some issues require further investigation, but it appears that devices can be used for network-level PMS applications.

Efforts are underway to develop the methodologies for incorporating the device measurements within PMS applications. In the development of these methodologies, the 3-D Move software is being used to identify or develop promising indices/parameters. The software has been calibrated based on the device and sensor data collected at the MnROAD facility and it is ready for use in the final effort of the study. Although the final outcomes are not ready, it is fully anticipated that indices/parameters will result for incorporation into network-level PMS applications and they will be ready prior to the conference.

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