UK Trial to compare 1\textsuperscript{st} and 2\textsuperscript{nd} Generation Traffic Speed Deflectometers

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Abstract

A comparative trial between two different versions of the Traffic Speed Deflectometer, that measures the deflection response of road pavements whilst surveying at traffic speed, has been carried out on a closed trial site in the UK and on adjacent in-service roads in October 2013. The objectives of the trial were to assess the relative performances of the 1\textsuperscript{st} vs 2\textsuperscript{nd} generation machines in terms of measured levels of deflection response, together with the repeatability and stability of the measuring components. Two of the machines, those from Denmark and the UK, were first generation machines and the third from Italy was an example of a second generation machine. The main aim of the trial was to provide guidance to the owners, in particular Highways England, on the potential benefits of upgrading a 1st generation machine. (135 words)

Keywords: road pavement assessment, structural condition, deflection, traffic-speed measurement, Traffic Speed Deflectometer (TSD).

1. Introduction

The deflection measurement remains the only reliable non-destructive method for determining the structural strength of in-situ flexible and flexible-composite pavements. Conventionally, this involves the measurement of pavement deflection by two devices, namely the Deflectograph and the Falling Weight Deflectometer (FWD). Both these devices provide a stationary frame of reference relative to which pavement deflections are measured. However, these methods employ slow-moving (Deflectograph) or static measurement (FWD) techniques that are expensive to operate, potentially hazardous for operators and cause disruption to the road users.

The development of the Traffic Speed Deflectometer (TSD), jointly by Greenwood Engineering and the Danish Road Directorate (DRD) in the late 1990’s and early 2000’s, provides a method for determining the structural condition of road pavements at traffic speed and offers a potential solution to minimize or remove the risk associated with the static and slow deflection measurement devices. Traffic speed surveys can minimize delays to road users and lower cost of surveys with improved and safer coverage of the network.

The UK Highways Agency (now Highways England (HE)) acquired one of the two 1st generation (1G) TSDs in 2005. Following which TSD research was commissioned from TRL by the HE which established a basic empirical relationship between measurements from one of the TSD lasers and Deflectograph measurements. This relationship was used within the framework of the existing standard UK Deflectograph structural maintenance design method. The research findings enabled TSD to be used as a network assessment tool capable of measuring deflection response of flexible road pavements at traffic speed and deriving four levels of Network Structural Condition (NSC) categories. As a result of this development work, routine network level structural condition surveys of the English Strategic Road Network (SRN) with the TSD were successfully implemented in 2010 under the first TRASS
(Traffic Speed Structural Condition Survey) contract (TRASS1). Two further similar contracts have followed, TRASS2 and the current TRASS3.

However, the Highway England TSD is now nearly 10 years old and the manufacturer, Greenwood Engineering A/S, has now enhanced their design using more advanced technologies in their later TSD models. Therefore HE is now considering the possibilities for upgrading their machine into a second generation (2G) TSD. Consequently, in order to inform Highways England, TRL has been commissioned to investigate the performance and likely benefits of the 2G TSD in comparison to the 1G TSD.

This paper describes part of such an investigation. In order to carry out the assessment and evaluate the TSDs, side-by-side testing under similar road conditions was necessary. To accomplish this, a structured comparative trial was conducted by TRL in September 2013 on HE’s experimental test sections at the MIRA proving grounds (www.miratechnologypark.com) and nearby in-service road pavements.

2. Description of trial equipment and test locations

2.1 Traffic Speed Deflectometers

Figure 1 shows the three TSD’s that took part in the comparative trial. The DRD and HE machines are both first generation versions. The 1G TSD is a deflection measurement device mounted on an articulated truck with four Doppler lasers attached to a rigid steel beam whose height is controlled by servo-hydraulics according its height from the pavement surface. The lasers measure the vertical deflection velocity of the pavement surface generated by the loaded rear axle at traffic speed. The rear axle wheel load is 100KN when fully loaded. Three measurement lasers are positioned at 0.1m, 0.3m and 0.75m (for the HE machine) and 0.1m, 0.2m and 0.3m (for the DRD machine) in front of the rear loaded axle, and a fourth Doppler laser, designated as the reference laser, is positioned 3.6m in front of the rear axle. The position of the six measurement lasers for the 2G ANAS machine are 0.1, 0.2, 0.3, 0.6, 0.9 and 1.5m in front of the rear axle together with a reference laser at 3.6m. The reference laser, due to its location roughly midway between the trailer and the rear loaded axles, is expected to measure minimal vertical pavement deflection velocity and is used to remove any unwanted signals due to the vehicle movement from the measurement lasers. The DRD and ANAS TSDs uses a separate odometer wheel to measure distance, whereas the HE TSD uses a further Doppler laser sensor to measure distance. Each of the machines has been described in more detail by Baltzer (1) for the DRD machine, Ferne (2) for the HE machine and
Cesolini (3) for the ANAS machine. Information on the latest design of TSD can be found on the manufacturer’s website (4).

The Doppler lasers are mounted at an approximate angle of \( \approx 2^\circ \) from the vertical to allow a constant velocity input from the horizontal vehicle velocity while having little effect on the vertical speed component. It is not practical to mount the lasers at a precise angle of \( 2^\circ \) because of configuration constraints central to the construction of the laser, corrections must be made to take account of the differences in angles based on geometric calibrations.

2.2 Test locations

In order to allow a comprehensive assessment and comparison of the TSDs, it was felt necessary to collect data under similar conditions on controlled test sections and also on a range of in-service pavements. The HE’s experimental test sections at the MIRA proving grounds were selected as the controlled test sections together with a range of in-service pavement lengths near to MIRA. The test locations are further detailed in the following paragraphs.

The experimental test sections at MIRA were constructed in 2010 by TRL on behalf of HE. The test sections are located on the twin horizontal straights (THS) at MIRA and are 595m long in total consisting of 6 homogeneous construction sections. Sections TT1, 2 and 3, each 70m long, were all of fully flexible construction of progressively weaker construction, with TT1 having nominally 265mm of asphalt material with a stiff binder on a stabilised sub-base, TT2 comprised 205mm of similar asphalt material to TT1 on a good quality granular sub-base and TT1 included a similar 200mm thickness of asphalt material but with a much software binder and a poor quality granular sub-base. The remaining test sections TT4 to 6 comprised the existing 230mm jointed reinforced concrete with a 40mm asphalt surfacing. The outer wheel path of the test sections TT1, TT2 and TT3 are installed with gauges to measure strains at the bottom of the asphalt base and on the top of the subgrade. Temperature sensors are also installed in these three sections to continuously record surface, air and pavement temperatures at three different depths (40mm, 100mm and 200mm).

In order to enable comparison of TSDs on a range of in-service pavements typical of the HE network, sections of primary roads and motorways close to MIRA totalling 48km in length were tested by all three TSDs. Three test runs were conducted on sections S1, S2, S3A and S10 by all the TSDs testing in convoy and these were used in the repeatability analysis and comparison.

3. Execution of the comparative trial

The objective was to carry out all the comparative surveys during the period 21 to 24 October. However, due to unforeseen weather conditions and some technical failures, changes were made to the original program in order to achieve the set objectives.

During the trial, it was discovered that the height sensing laser on HA’s TSD was damaged and was not responding to the changes in the road surface profile. The output from this laser is used to try and ensure that the Doppler lasers are at the optimal height from the road surface in terms of focus. On examining the data, it was found to be unreliable with extreme unsystematic variations in the deflection slopes, therefore it was considered not sufficiently reliable to be used in this study. Data collected previously by the HE TSD at the MIRA site, that was unaffected by the unreliable height sensor, was screened for similar temperatures as recorded during the trial. Unfortunately, no data was found that was collected at similar temperatures to those of the comparative trial. For comparative purposes, the HE TSD data
collected on the 24\textsuperscript{th} June 2013 at similar speeds but at higher temperatures were used for the analysis.

4. Results of comparative TSD studies

4.1 Geometric calibration

The accuracy and consistency of the geometric calibration of the TSDs, in order to determine the relative angles of the Doppler lasers, is vitally important as it can have significant impact on the deflection slopes derived from the laser velocity measurements. An important aspect of the comparative trials was therefore to review the angle calibration procedures of the 1G and 2G TSDs and compare the consistency of the calculated calibration angles. The calibration procedures for the 1G and the 2G TSDs are completely different. The 1G TSDs have a fixed beam, in terms of longitudinal position, to which the lasers are mounted and use a ‘load on and off’ method originally recommended by the manufacturer to determine the relative laser angles. In contrast, the 2G TSD has Doppler lasers mounted on a movable beam, that enables a more sophisticated and improved calibration process by progressively moving the beam longitudinally across multiple test runs so that the pavement response can be measured at different offsets from the axle load.

A comparison of the calibration angles computed using tests conducted on the same day from two different rigid pavement sections by the three TSDs was made. For the ANAS TSD the sensors showed a maximum variation of 0.003 degrees during the tests, which is equivalent to roughly 60\% of the interval between NSC categories. In contrast both the DRD and HE 1G TSD’s showed variations of up to 0.007 degrees during similar tests, equivalent to 140\% of the average NSC category interval.

4.2 Repeatability

An important measure of the relative capabilities of the machines being assessed was considered to be their short term repeatability characteristics. This was expressed in terms of the standard deviation of repeat measurements, normally 5 or 6 runs, of the average deflection slope of each 10m length for the two Doppler sensors with the same location relative to the rear axle on each TSD, i.e those nominally 100 and 300mm in front of the rear axle, coded P100 and P300. Since the Danish and Italian TSD’s measure deflection slope in the right hand wheelpath and the HE machine measures in the left hand wheelpath comparisons of all three machine measurements was only possible on the closed test sites by surveying in opposite directions. The results for the closed tests sections at MIRA have therefore been reported separately from those on the in-service road lengths.

4.2.1 MIRA test sections

Figures 2 to 4 show the variation in deflection slope every 10m for the six MIRA test sections for each of the repeat runs together with the 10m standard deviation of repeatability for the ANAS, DRD and HE TSD’s respectively. All these surveys runs were carried out at a nominal 70 km/h. It should be noted that, as explained earlier in Section 3, the results for the HE machine were obtained from an earlier date when the pavement temperature was higher than at the main trial. As the DRD and ANAS TSD’s surveyed in the reverse to the normal survey direction, the longitudinal location of the results from these machines have been reversed to make them more directly comparable with the HE results.

Table 1 provides the average repeatability standard deviations for each of the machines for each of the MIRA test sections. This shows very similar values for the ANAS and DRD machines but slightly higher values for the P100 sensor on the HE machine.
Figure 2. 10m P300 results from repeat runs of ANAS TSD on 23 October 2013

Figure 3. 10m P300 results from repeat runs of DRD TSD on 23 October 2013

Figure 4. 10m P300 results from repeat runs of HE TSD on 24 June 2013
Table 1. Summary of Repeatability SD ($SD_r$) – MIRA outer wheelpath

<table>
<thead>
<tr>
<th>TSD Sensor</th>
<th>SD$_r$ for each MIRA test section ($\mu$m/m)</th>
<th>Machine</th>
<th>TT3</th>
<th>TT1</th>
<th>TT2</th>
<th>TT4</th>
<th>TT5</th>
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<td>45</td>
<td>44</td>
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</tr>
<tr>
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<td>DRD</td>
<td>40</td>
<td>43</td>
<td>41</td>
<td>54</td>
<td>37</td>
<td>35</td>
<td></td>
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<td>HE*</td>
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<td>59</td>
<td>53</td>
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<td>53</td>
<td>42</td>
<td>28</td>
<td>30</td>
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</table>

* Data collected on earlier date at higher temperature.

4.2.2 In-service road pavement lengths

The pavement test length at MIRA is relatively new and is not trafficked regularly, as it is not a part of the public road network. This could mean that its response is significantly different from the response of the typical in-service pavements on the Strategic Road Network (SRN) of Highways England. TSD repeat tests were therefore carried out on four selected in-service pavement lengths (48km) of the HE network close to the MIRA site. All tests were performed at nominally 70kmph by the three TSDs following back to back as much as possible. Due to the issues with the operation of the HE TSD discussed earlier, data collected by this machine during the comparative trials was not used in this report. However, for the repeatability analysis, data collected from the same sections on a different day (in June 2013) was used.

Table 2. Summary of repeatability SD ($SD_r$) – In-service pavements

<table>
<thead>
<tr>
<th>TSD sensor</th>
<th>Machine</th>
<th>SD$_r$ for each in-service test length ($\mu$m/m)</th>
<th>S-1</th>
<th>S-2</th>
<th>S-3A</th>
<th>S-10</th>
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<td>DRD</td>
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<td>HE*</td>
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<td></td>
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<td>1.1</td>
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<td>DRD</td>
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<td>77</td>
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</tr>
<tr>
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<td>HE*</td>
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<td>82</td>
<td>112</td>
<td>-</td>
<td></td>
</tr>
<tr>
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<td>1.6</td>
<td>1.1</td>
<td>1.4</td>
<td></td>
</tr>
</tbody>
</table>

*Data collected on earlier date at higher temperature on other wheelpath
Table 2 provides the average repeatability standard deviations for each of the machines for each of the four in-service test lengths calculated in the same manner as used for the MIRA test sections. However, it should be noted that the ANAS and DRD machines measured in the inner wheelpath of lane one and the HE TSD in the outer wheelpath so the results are not directly comparable. DRD results are between 10% and 70% higher than the ANAS results with an average figure of 40% higher.

4.3 Consistency between TSDs

One of the objectives of this trial was to assess the comparability between the levels measured by the different machines. The side-by-side repeat runs on the test sections at the MIRA site provided an opportunity to assess this consistency. The mean P300 10m slope values of the repeat test runs for each of the three TSDs are shown in Figure 5.

![Figure 5. P300 mean slope profiles for all machines in outer wheelpath at MIRA](image)

However, due to the poor data quality from the HE TSD at the time of the trial the results presented for this machine are from an earlier date at a higher temperature. If we assume that all the machines should read at a similar level on the strong overlaid concrete sections then it is possible to apply corrections factors to the DRD and HE results to compensate for differences which may have been caused by incorrect geometric or distance calibrations. Figure 6 shows the results of incorporating these corrections together with an appropriate adjustment for the difference in survey temperatures. The results confirm the similarity of the characteristic shape or profiles measured by the three different machines.
Figure 6. P300 mean slope profiles for all machines after corrections

4.4 Relationship with other deflection measuring devices

Figure 7. TSD P300 slope vs FWD central deflection (10m averages)
Although the three devices TSD, FWD and Deflectograph all measure the deflection response of the underlying pavement to load, they are not directly comparable as the types of loading and the methods of measurement are significantly different. However, it is instructive to assess the level of correlation between the TSD and both the FWD and the Deflectograph as the latter two devices are currently used in the UK and elsewhere to assess the condition of existing pavements for maintenance and rehabilitation purposes, and engineers have gained much experience in their effective interpretation. As Deflectograph and FWD data were not collected during the comparative trial, previously collected data at similar pavement temperatures as recorded at the time of the comparative trial were used for the assessment. Many comparisons were made but just one example is presented in this paper. Figure 7 shows the relationship between the 10m mean P300 slope value for all three TSDs against the comparable central FWD deflection. The correlation coefficients ranged from 0.84 to 0.89 for the different machines with standard errors of estimate ranging from 46 to 69 μm/m.

4.5 Relationship between measured and predicted pavement strains

An important element of the comparative trials was to assess the estimated asphalt strains derived from the TSD measurements against the asphalt strains recorded by gauges installed in the pavement test sections at MIRA. It is notoriously difficult to obtain robust reliable strain from gauges installed during pavement construction. The first stage of this comparison therefore involved an assessment of the quality of the outputs from the working gauges based on estimated values, using linear elastic forward modelling, and actual measurements under FWD loading, a more predictable loading situation than a rolling wheel moving at survey speed. The final stage was to compare available realistic strains measured at the comparative trial against those estimated from the TSD measurements. Figure 8 illustrates these results using the strains modelled with a simple elastic model under a standard 50kN FWD load as the reference values on the x-axis. Those strains predicted from the measurements by the DRD and HE machines have not been included as some of these were unrealistic negative values.

![Figure 8. Comparison of measured and predicted asphalt strains on MIRA test sections](image-url)
The results shown in Figure 8 are very encouraging as a preliminary result since little effort has been made to exactly model the materials, thicknesses and conditions of the structures and the operating conditions on the day of the test. The Figure shows that all the methods rank the strains in the same manner. Thus the results suggest that the TSD has the potential to be used to predict horizontal strains at the bottom of the asphalt layers, much as the FWD is often used, but that an improved model is required to improve the accuracy of the prediction.

5. Conclusions

A comparative study of the 1G and 2G Traffic Speed Deflectometers (TSD) has been carried out in October 2013 at the MIRA proving grounds near Nuneaton, UK and on in-service roads close to the site using three different TSDs, two 1G TSDs from England and Denmark and one 2G TSD from Italy. In summary, despite the limitations of this study, due to poor weather conditions and equipment failure, the trial has shown that the 2G Traffic Speed Deflectometers have better repeatability, less variable calibrations and better potential for strain prediction within the pavement in contrast to the 1G models. In addition, the trial has emphasized the two key factors to obtaining acceptable measurements from such equipment namely: dry surface conditions and stable correct and up-to-date geometric calibration of the equipment. The study has also confirmed that this latter calibration requirement is more effectively met by the 2G TSD.

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