

# Structural pavement monitoring with non-destructive measuring devices – Experiences from a pilot project in Germany

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**ABSTRACT:** Within the last 20 years, Germany's federal road network of 53,000 km has become the centre of transit road freight transport in Europe. As a large part of the network is now about 30 to 50 years old, a systematic pavement and maintenance management becomes more and more essential for road authorities.

The existing German pavement condition monitoring and assessment and Pavement Management System (PMS) focuses on measured surface characteristics like longitudinal and transverse profile, skid resistance and visual damages like cracking, spalling, patching, bleeding and is conducted in a four year cycle on the entire federal road network. A pavement condition rating based on these surface characteristics is calculated using a standardised procedure. No account is taken for structural bearing capacity and often there is poor knowledge about the pavement structure, layers and thicknesses. As Falling Weight Deflectometer (FWD) deflection measurements and coring are suitable measures for project level assessments and require lane closures, there is a growing demand for Non-Destructive-Testing (NDT) methods on network level at highway traffic speed without traffic disruptions.

To overcome the lack of knowledge about the structural condition and the need to detect structural pavement deteriorations, the German Federal Highway Research Institute (Bundesanstalt fuer Strassenwesen - BASt) conducted a project where NDT systems operating at traffic speed of 80 km/h like the Ground Penetrating Radar (GPR) and the Danish Traffic Speed Deflectograph (TSD) performed concerted measurements on selected highway and trunk road sections. The testing was supplemented by FWD measurements and core samples.

In the following, an overview over the state-of-the-art in pavement condition monitoring and the results of NDT measurements will be given as well as an assessment of different structural pavement parameters. The observed problems and shortcomings and the advantages and possibilities of the different techniques for structural pavement condition assessment will be addressed and discussed.

**KEY WORDS:** Structural pavement monitoring, Falling Weight Deflectometer FWD, Traffic Speed Deflectograph TSD, Ground Penetrating Radar GPR

## 1 INTRODUCTION

### 1.1 Pavement condition monitoring in Germany

The pavement condition monitoring and assessment on Germany's 12,000 km federal highway and 41,000 km trunk road network is carried out in a four year cycle. Longitudinal and transverse profile, skid resistance and surface images are continuously recorded with measuring vehicles at traffic speed. Profile data is recorded every 1.0 m with longitudinal

profile measured in the right wheel track. A virtual water level is computed from the measured rut depth and the transverse slope for asphalt pavements. A spectral density analysis is performed on the longitudinal profile data resulting in the general unevenness index AUN (Allgemeiner Unebenheitsindex). Skid resistance is recorded by the SKM-device (Seitenkraftmessgerät) which is based on the SCRIM principle. A structural surface condition index is calculated from the visual image data on the basis of surface crack length and areas affected by damages like patches, spalling and ravelling per unit length or unit area.

The calculated values are then normalised and transformed into marks from 1 to 5, with 1 rating a very good and 5 rating a very poor pavement condition. These marks are then averaged to form homogeneous 100 m sections. The final result is a condition map showing the rating from 1 to 5 for each condition parameter in 100 m resolution for the entire federal highway network. This data serves as input for the PSM and the planning of maintenance measures.

## 1.2 Traffic Speed Deflectograph TSD

The High Speed Deflectograph (HSD) device was originally developed by the Danish company Greenwood in cooperation with the Danish Road Institute (DRI). The name was later changed to Traffic Speed Deflectograph (TSD) for public relation reasons. The TSD is a measuring vehicle comprising a twin-tyred single-axle trailer carrying a container with measuring equipment towed by a two axle prime mover as shown in Figure 1.

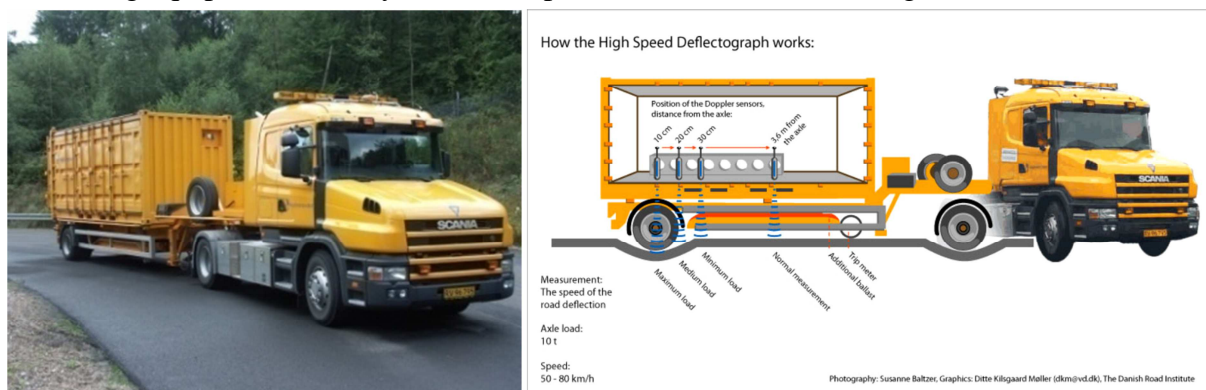


Figure 1: The Danish Traffic Speed Deflectograph and the measuring principle.

The static vertical wheel load of the trailer axle is about 10 t with 5 t on each wheel. Four Doppler laser sensors are installed on a rigid steel truss beam inside the container at an offset of 100, 200, 300 and 3,600 mm in front of the vertical centre axis of the trailer axle. Three sensors at 100, 200 and 300 mm offset measure the surface deflection velocity induced by the vertical wheel load of the trailer axle. The sensor at 3,600 mm offset works as reference sensor for compensating the vertical body movement, presuming no deflection occurs in this area due to ample spacing between the adjacent axles.

Finally, the centre deflection  $D_0$  and the Surface Curvature Index SCI300 are computed using either a polynomial fit or an elastically bedded beam model. Additionally, air and road surface temperatures are measured and GPS signals can be recorded. The normal operating speed of the TSD is between 50 and 80 km/h. Measurements at 40 km/h have also been conducted successfully. More detailed information about the TSD can be found amongst others in Rasmussen, S. ; Krarup, J. A. ; Hildebrand, G. (2002), Rasmussen, S. (2008), Ferne, B. et al. (2009a), Ferne, B. et al. (2009b) and Hildebrand, G. ; Rasmussen, S. (2002).

### 1.3 Falling Weight Deflectometer FWD

The FWD is a best-known pavement surface deflection measurement device used for structural pavement analysis and thus only briefly described here. The BAST FWD used for the measurements has nine geophones and all measurements in the framework of this project were carried out with 50 kN vertical target load at 7.5 m distance between measurement points on all nine test sections.

One common evaluation approach is to compute structural deflection bowl parameters from the measured values which are related to the structural strength/stiffness of different layers. A comprehensive selection of structural deflection bowl parameters is compiled and described in WSDOT (2005). In the framework of this project five structural deflection bowl parameters were computed, three of them were selected here to rate the structural strength of the upper asphalt layers of the pavement sections (D0, SCI300, Tz). The BAST FWD and selected deflection bowl parameters are shown in Figure 2.

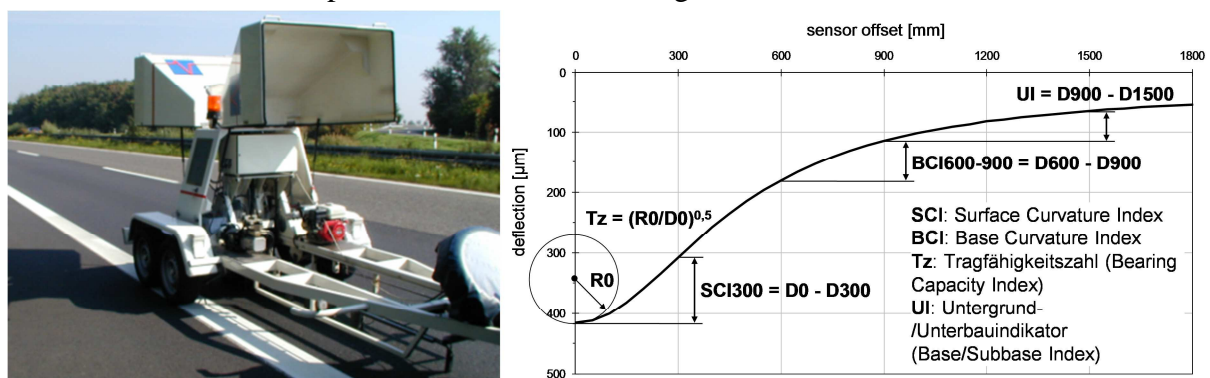


Figure 2: BAST Falling Weight Deflectometer FWD (left) and selected FWD deflection bowl parameters (right) for structural strength assessment of pavement structures.

### 1.4 Ground Penetrating Radar GPR

The Ground Penetrating Radar (GPR) is a non-destructive measurement system which is mainly used in geophysics and geotechnical engineering. The system is based on the propagation of electromagnetic waves and the reflection at layer interfaces in earth, soil and pavement structures. The measured propagation time can be related to the thickness of a layer inside a pavement structure by calibration. Sufficient knowledge and experience of the user presumed, GPR enables the detection of structural defects like voids or poor bonding of layers and the identification of different layers as well as their thicknesses.

As the wave propagation time and the wave reflection depends on the dielectric constants of the materials it is principally easier and more reliable to distinguish between bound and unbound materials like asphalt on a granular base (different dielectrical constants) than between layers of similar materials like asphalt base, asphalt binder and asphalt wearing course (similar dielectrical constants). In the framework of this project, GPR measurements were performed to identify the different layers as far as possible and to continuously determine the total thickness of the bound layers and their variation in thickness. An essential advantage of the GPR is that it can be operated non-destructively at traffic speed of up to 80 km/h with a high data acquisition rate providing a “continuous” image of a pavement structure. More detailed background information on the GPR can be found amongst others in Saarenketo, T. (1997) and Saarenketo, T. ; Roimala, P. (1998).

Figure 3 shows the BAST van-mounted GPR antenna and a detail of a radar diagram, indicating the different layers and their interfaces of a measured pavement section of the B35 trunk road in the framework of this project.

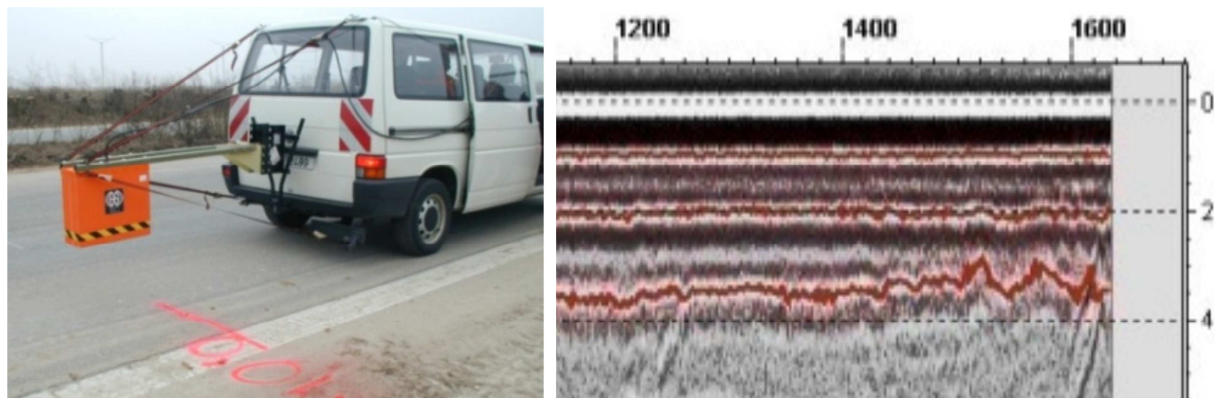


Figure 3: BASt van-mounted GPR antenna (left) and radar diagram of the B35 trunk road indicating different pavement layers and their thicknesses (right).

## 2 CHARACTERISTICS OF THE SELECTED TEST SECTIONS

Four federal highway sections and five federal trunk road sections were chosen for the comparative measurements with FWD, TSD and GPR. The structure and layer thicknesses of the highway sections A3 and A70 were taken from a research report by Ressel, W. et al (2008) which contains evaluation of core samples as well. Additional core samples were taken in all sections of the B35 federal trunk road for laboratory testing. Except for the A70 the GPR total asphalt thickness matches very well with the core thickness. Table 1 summarizes the basic data of all nine pavement sections selected for this project.

Test section		A3 Wies- baden	A3 Fuerth	A3 Nuern- berg	A70 Stadel- hofen	B7 West- uffeln	B35 Illingen 1	B35 Illingen 2	B35 Illingen 3	B35 Illingen 4
Section length	[m]	500	500	500	500	400	400	400	400	400
Age	[yrs]	21	28	28	16	n.a.	1	1	1	1
Base <sup>1)</sup>		UG	CEM	CEM	UG	UG	UG	UG	UG	UG
Class <sup>2)</sup>		SV	SV	SV	SV	II	II	IV	III	III
Min ESALs ( $B_{min}$ ) <sup>3)</sup>	[mio]	32	32	32	3	3	3	0,3	0,8	0,8
Max ESALs ( $B_{max}$ ) <sup>3)</sup>	[mio]	100	100	100	10	10	10	0,8	3	3
HV share	[%]	18,3	18,9	17,8	19,0	n.a.	17,7	17,7	17,7	17,7
AADT <sup>(HV)</sup>	[V/24h]	10,168	16,999	19,148	4,652	n.a.	1,512	1,512	1,512	1,512
$B_{accumulated}$	[mio]	30,124	57,195	64,425	12,162	n.a.	0,389	0,389	0,389	0,389
$B_{accumulated} / B_{min}$	[-]	0,94	1,79	2,01	0,38	n.a.	0,13	1,32	0,50	0,50
$B_{accumulated} / B_{max}$	[-]	0,30	0,57	0,64	0,12	n.a.	0,04	0,50	0,13	0,13
AC top layer (core)	[cm]	4,0	4,0	4,0	4,0	4,7 <sup>4)</sup>	4,0	4,3	4,5	4,1
AC binder (core)	[cm]	8,0	4,0	7,0	9,0	5,0 <sup>4)</sup>	7,5	-	8,2	8,0
AC base (core)	[cm]	22,0	17,5	24,5	14,0	3,6 <sup>4)</sup>	10,3	10,5	9,1	8,2
sum asphalt (core)	[cm]	34,0	25,5	35,5	27,0	26,0 <sup>4)</sup>	21,8	14,8	21,8	20,3
mean asphalt (GPR)	[cm]	34,2	25,7	33,8	32,6	-	20,4	14,7		20,2
asphalt (design)	[cm]	34,0	26,0	26,0	26,0	-	22,0	15,0		20,0

<sup>1)</sup> UG = Unbound Granular, CEM = Cement Treated Base on granular base

<sup>2)</sup> Construction Class according to the German Pavement Design Guideline RStO

<sup>3)</sup> 10t-ESALs according to the German Pavement Design Guideline RStO

<sup>4)</sup> asphalt pavement comprises seven layers, only three layers are shown

Table 1: Basic data of all nine pavement sections.

### 3 MEASUREMENT RESULTS

#### 3.1 GPR Measurements

The main objective of the GPR measurements was the continuous identification of structural layers and the determination of the total asphalt thickness and the thickness of the cement bound base courses underneath if present.

Figure 4 shows a typical radar diagram of the four different sections of the B35 trunk road with layer interfaces marked on the basis of the wave reflection at the layer interfaces (red lines). Due to the strong reflection, the layer interfaces between asphalt and granular base could have been determined with reasonable accuracy and correspond well with the core data.

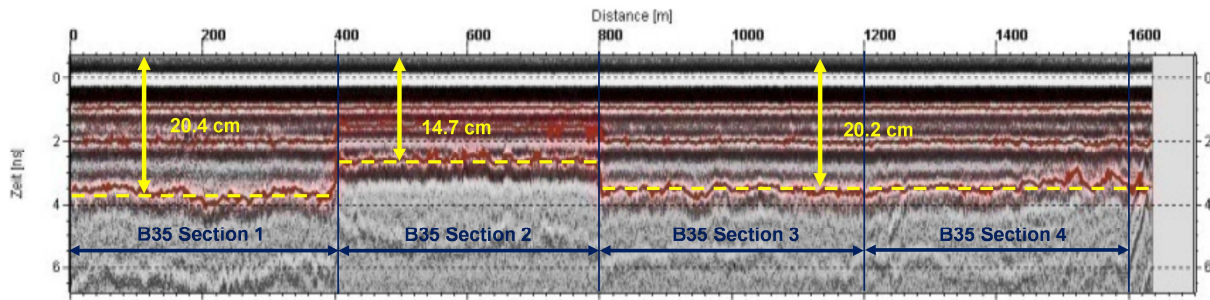


Figure 4: GPR radar-diagram of four different pavement sections of the B35 trunk road at Illingen indicating the total asphalt thickness (mean value) and the layer interfaces.

The comparison between mean GPR total asphalt thickness and total asphalt thickness determined on cores (Figure 5) show a very good agreement except for the A70 section. The reason for this is considered an incomplete core due to the reported poor bonding of layers.

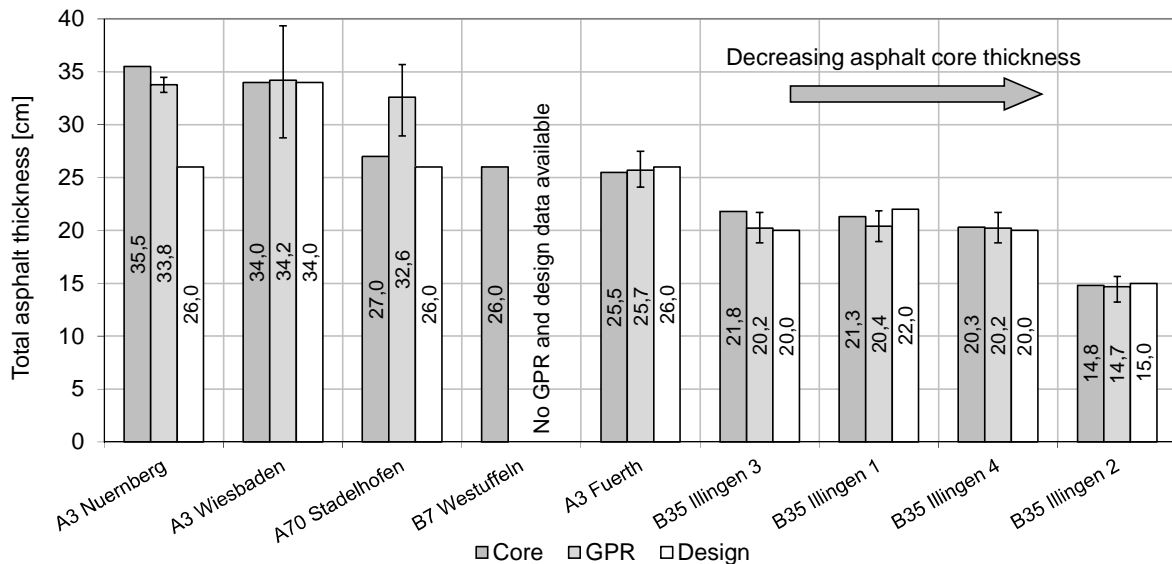


Figure 5: Comparison of total asphalt thickness determined from GPR measurements (mean, 5% and 95% quantile) per section, asphalt cores and (assumed) design thickness.

#### 3.2 FWD Measurements

FWD measurements were taken at intervals of 7.5 m on all test sections. Figure 6 shows the FWD D0 and FWD SCI300 mean values, the 5% and 95% quantile per section, the total asphalt core thickness and the average surface temperature during the measurements.

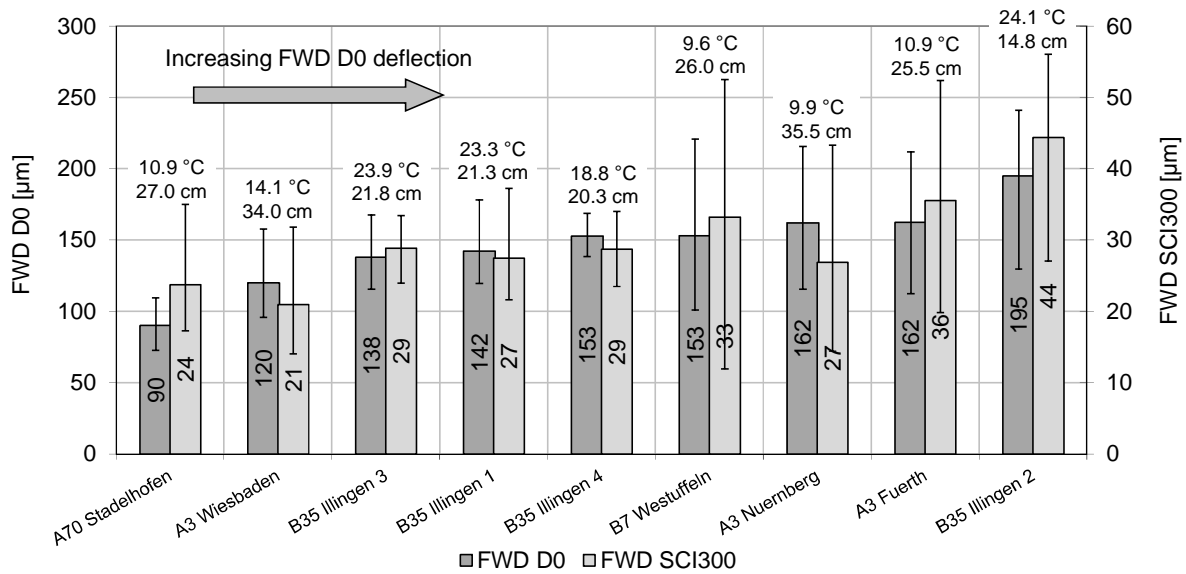


Figure 6: FWD D0, FWD SCI300, asphalt core thickness and average surface temperature.

Both, FWD D0 and FWD SCI300 values show a relatively high scatter of stiffness in almost any section except the B35 sections 1, 3 and 4 while the scatter of D0 is generally less than the scatter of SCI300. The deflection values are not compensated for temperature. It should be mentioned that the surface temperature during the measurements on the B35 is about 11 °C higher than in the other sections and therefore the strength of the B35 sections based on the FWD deflection values might be slightly underrated. The development of a temperature compensation procedure based on stiffness from asphalt master curves derived from dynamic laboratory testing is currently in progress at BASt.

Both parameters indicate a similar strength ranking for all test sections. According to these values the A70 highway section and the A3 section at Wiesbaden are rated the strongest pavements although both pavements do not comprise any cement bound base underneath the asphalt as the A3 Fuerth and A3 Nuernberg sections. Due to the high scatter there are some overlaps in the range of values between pavement sections of different mean strength and construction class. B35 section 2 shows the highest deflection values – obviously due to the lowest total asphalt thickness of all pavement sections.

### 3.3 TSD Measurements

All TSD measurements are generally characterized by very high scatter of the calculated TSD SCI300 parameter. The Danish Road Institute also noticed an offset and a drift of the TSD data on the B35 due to an uneven warming up and bending of the measurement beam inside the container because of a warming up of the lasers according to Baltzer, S. (2011). Thus, the B35 measurements have to be treated with caution and are not fully evaluable.

All TSD measurements also produced a remarkable amount of negative TSD SCI300 values. Negative TSD SCI300 values can theoretically be explained by measurements on a pavement stiffer than the pavement the calibration of the TSD lasers was carried out on as mentioned in Ferne, B. et al. (2009a). In the present case, negative SCI300 values occur even on a relatively weak pavement as the B35 section 2 with only approx. 15 cm of total asphalt thickness. However, the reasons for the negative TSD SCI300 values are not yet identified.

Figure 7 shows the TSD SCI300 for all four B35 sections with raw data of 0.1 m resolution and computed 5 m and 10 m moving average. Section 2 can be easily identified as the weakest section with 15 cm asphalt compared to the other sections with an average total asphalt thickness of 20-21cm.

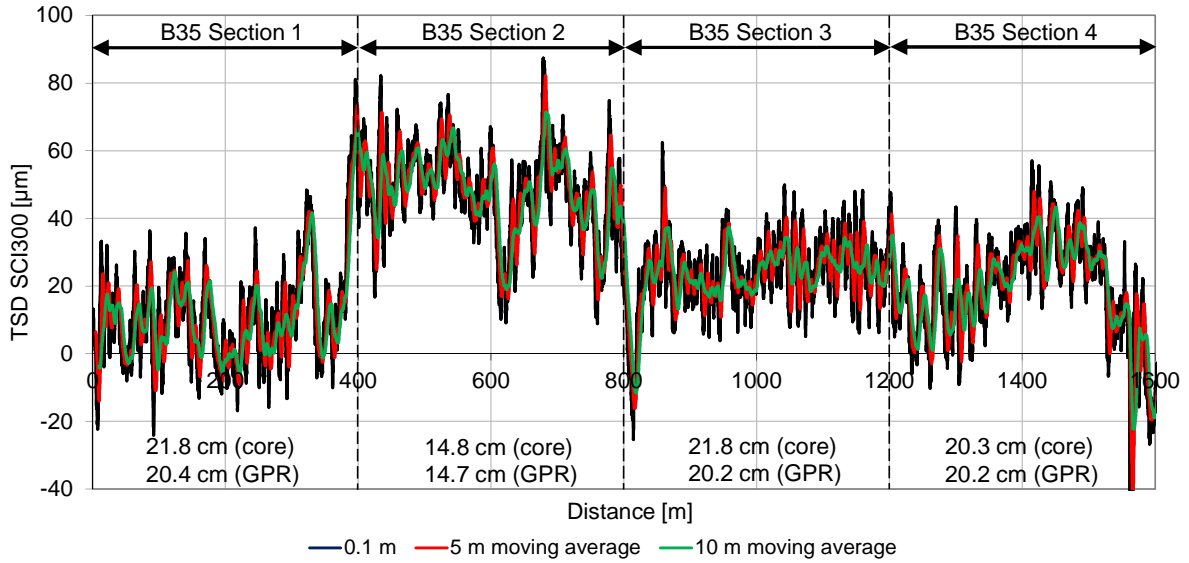


Figure 7: TSD SCI300 of all four sections of the B35 Illingen federal trunk road at different moving average values at an average surface temperature of 16.3 °C.

Despite of the obvious difficulties a pragmatic evaluation approach of the TSD SCI300 data was performed by computing the mean values of each measurement run per section (Figure 8), additionally indicating the average surface temperature and the total asphalt core thickness. The data has not been compensated for temperature.

The results show an adequate repeatability of the measurements only on the A3 Fuerth, the A3 Nuernberg and the B7 section. All other sections are characterised by an increase of the TSD SCI300 mean value for each run, indicating the aforementioned problem with the warming up and bending of the beam which causes erroneous results.

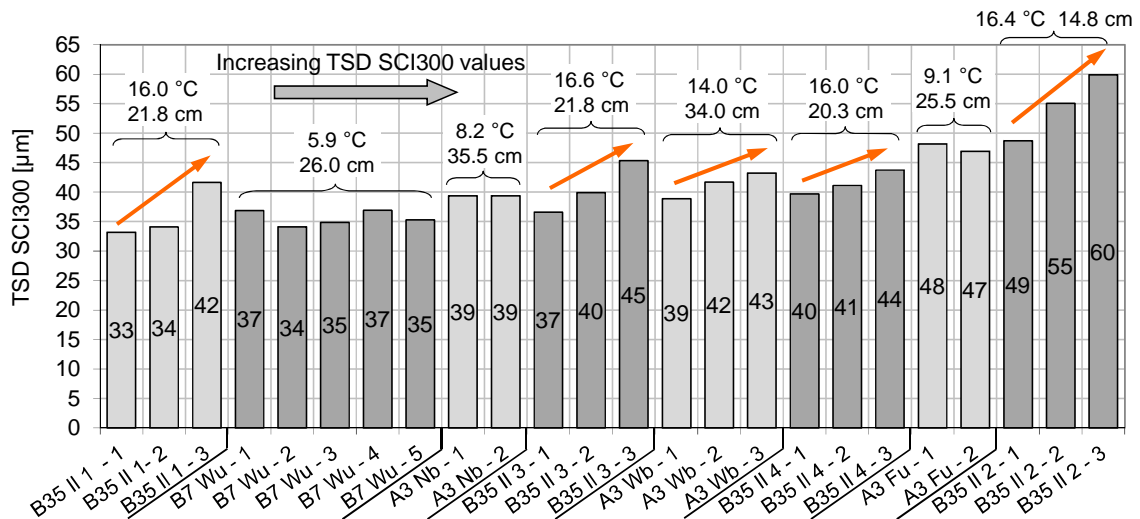


Figure 8: TSD SCI300 mean values, asphalt core thickness and average surface temperatures per measurement run (arrows indicate an increase due to temperature issues).

#### 4 COMPARISON OF TSD AND FWD PARAMETERS AND PAVEMENT STRENGTH RATING

For a final strength rating of the pavement sections the deflection parameters FWD D0, FWD SCI300 and FWD bearing capacity index Tz as well as the TSD SCI300 value are compared.

For each parameter the mean value along each test section is computed. Due to their different loading conditions FWD SCI300 and TSD SCI300 are different in nature.

The TSD SCI300 is calculated as mean value of up to three repetitive measurements along each test section with only positive SCI300 values being considered while unreasonable negative values were deleted. To simplify the comparison between the different pavement sections and the measurement devices neither homogeneous sections regarding thickness or deflection values within each test section nor the effect of different surface temperatures at the time of measurement were considered. The GPR measurements show that the structure in all sections remains the same along the test length and does not show significant variations in layer thickness so all sections are considered homogenous regarding their structure.

The FWD SCI300 and the TSD SCI300 are compared in Figure 9, including the average surface temperature and the total asphalt core thickness.

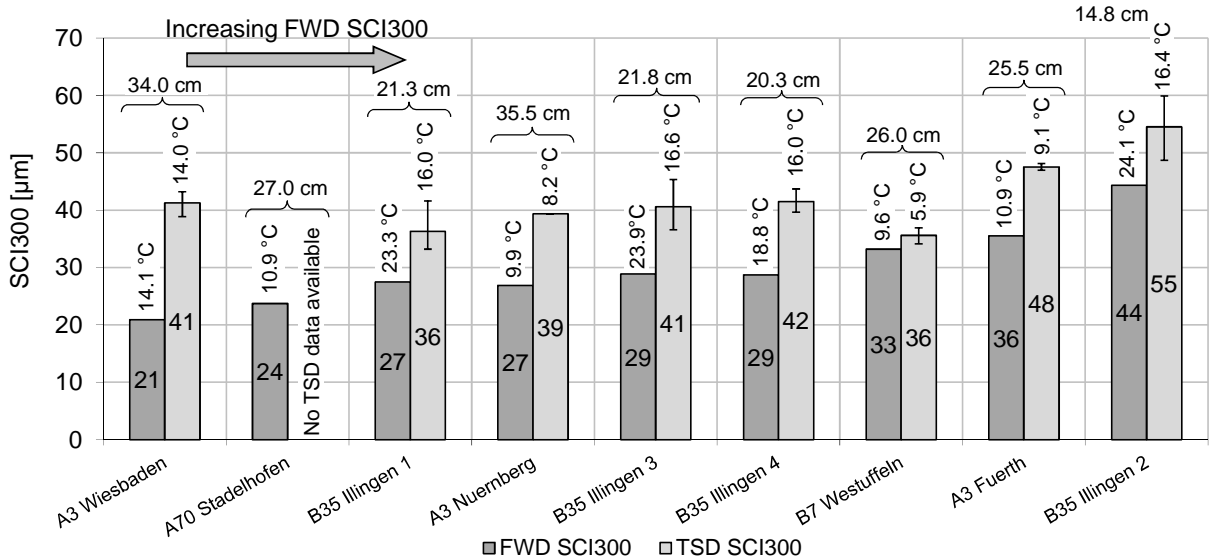


Figure 9: FWD SCI300 and TSD SCI300 (mean, min and max - all runs) values, average surface temperatures and total asphalt thickness per section.

Firstly, it can clearly be seen that the TSD SCI300 mean values are generally higher than the FWD SCI300 values for all sections. Secondly, the TSD SCI300 values indicate a different structural strength ranking than the FWD SCI300 values. Note that both values are not directly comparable due to their different nature. On the basis of these values the test sections show a different strength rating for each parameter and measuring device. The FWD parameters show a similar strength rating of the sections, identifying A 70 Stadelhofen and A3 Wiesbaden as the strongest, B35 Illingen, section 2 as the weakest (obviously, because of the lowest asphalt thickness) and the remaining as mid-strength pavements. Contrary to this, the TSD SCI300 rated B35 section 1 and B7 Westuffeln as strongest pavements. B35 Illingen section 2 and A3 Fuerth were rated as the weakest sections in accordance with the FWD D0 and SCI300 values. Note that the TSD surface temperatures on B7 and B35 are much lower than those of the FWD measurements meaning that these pavement sections might be slightly overrated. Contrary to their strong asphalt package on cement bound layers, the A3 Furth and Nuernberg sections show higher deflection values than sections with lower asphalt thickness.

The evaluation generally shows the difficulties in accurate pavement strength rating based solely on deflection parameters. A distinction between pavements of various strengths seems to be possible with FWD measurements. The assessment based on the present TSD SCI300 values has to be treated with high caution due to high scatter, implausible negative values and drift of the values due to temperature effects during some measurements.



## 5 SUMMARY, CONCLUSIONS AND OUTLOOK

Following main conclusions can be drawn from the evaluation of the described project:

- The TSD features a high data resolution (values all 10 cm at 80 km/h), facilitating a quasi-continuous registration of pavement strength along a road section.
- Compared to almost all TSD-measurements in external studies the TSD-measurements in Germany were performed on relatively thick and therefore stiff pavements. Thus, the resulting values are very low and problems occurred with the data procession.
- During the measurements it was detected that a warming up of the lasers produced a temperature gradient in the beam causing the beam to bend and producing a data drift. According to the DRI the container was later equipped with an air condition unit and fans to eliminate this problem.
- The high scatter of the TSD values as well as the implausible negative TSD SCI300 is considered critical. An adequate reliable distinction between stronger and weaker pavement sections does not seem possible on the basis of the measurements in the framework of this project.
- Absolute TSD SCI300 can be significantly shifted by choosing the moving average interval. This is to consider for any comparison with other devices.
- Vertical dynamic wheel loads due to vehicle body and axle movements induced by longitudinal unevenness as well as lane change manoeuvres and driving in curves may produce vertical wheel loads significantly higher or lower than the static TSD wheel load of 5 t. Deviations of up to 50 % from the static wheel load are not negligible as they produce deviations of the deflection values of the same magnitude according to Rabe, R. (2011) and Rabe, R. (2012). A continuous measurement of the vertical dynamic TSD wheel load is therefore considered a must. Deflection parameters could then be normalised to a “standard” static wheel load with reasonable good accuracy.
- The SCI300 value of the FWD and the TSD are not directly comparable because FWD and TSD have different load configurations and are computed using different methods. The evaluation of the data in this project does not show any reliable correlation between FWD SCI300 and TSD SCI300.
- The review of external projects confirmed a good short-term repeatability of the TSD data as stated in Kelley, J. ; Moffatt, M. (2012). No sufficient data is available to confirm a good long-term repeatability. The evaluation of measurements in Germany could not confirm a good short-term repeatability due to non-quantifiable effects. Other research also indicates that numerous influences like speed or surface properties are not fully quantified yet as stated in Ferne, B. et al. (2009b).
- A structural pavement assessment solely on deflection values is naturally impossible. Knowledge about layers and thickness is essential. Therefore an assessment of the bearing capacity based on deflection values is best combined with GPR measurements or at least with information on the as-built structure documented in the control checks - as far as available.
- Based on this evaluation, a bearing capacity index derived from TSD measurements for integration into a PMS requires more investigation into the influence factors, the data quality and reliability and evaluation methods.

Under consideration of the results of completed projects, including TSD measurements and review of external projects it can be finally stated that the TSD is potentially capable to non-destructively and efficiently detect variations in pavement strength of asphalt pavement structures at traffic speed, especially when combined with GPR-measurements.

The measurements in Germany however showed problems in the reliability of data for a structural assessment of pavement strength as implementation into PMS under any condition. Before further measurements are performed, the influences of temperature, dynamic wheel loads, surface properties, calibration, evaluation and processing etc. have to be thoroughly examined, quantified and improved under consideration of German conditions.

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