Road and Transportation Research Association

Working Group Infrastructure Management

FGSV

Working Paper
Bearing Capacity of Asphalt Pavements

Part B 5
Traffic Speed Deflectometer (TSD) – fast moving measurement system: description of equipment, taking measurements

AP Trag Teil B 5

W 2

Edition 2015
Translation 2017

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Working Group Infrastructure Management
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Task Group: TSD

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Preliminary remark

The Working Paper TSD, Edition 2015, Translation 2017 have been drawn up by the task group TSD, Chairman: Dr.-Ing. Jansen, Bergisch Gladbach.

Table of contents

1 General remarks

The “Traffic Speed Deflectometer” (TSD) is a fast-moving measurement system to record readings which can then be used as the basis for specifying the bearing capacity of asphalt pavements. The state-of-the-art method for measuring asphalt construction is presented below.

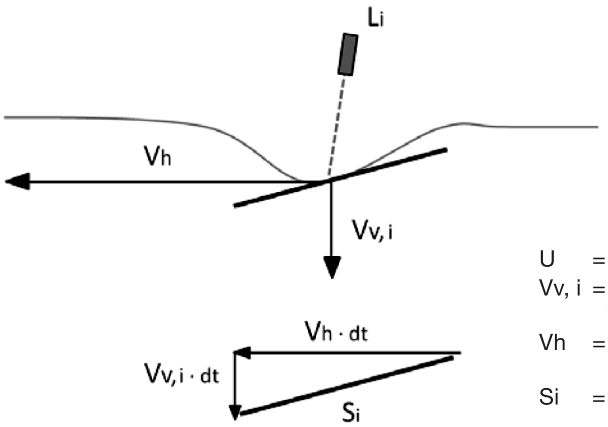
2 Description of the measuring method and measurement vehicle

2.1 Description of the measuring method

The measuring method consists of a truck (towing vehicle) with a single axle semi-trailer containing the measuring equipment. At the centre of the measuring equipment are several sensors (Doppler lasers) arranged at defined distances on a measuring beam and which are aligned almost vertically to the road surface. They continually measure the velocity of the brief surface deflection of the asphalt pavement in the direction of the sensors that results from the load caused by the trailer axle. The deflection velocity vector vertical to the road surface is established using the vector relationship arising from the measured deflection velocity vector (in the direction of sensors), the horizontal driving velocity relating to the measurement vehicle (corresponding to the measured speed of the vehicle) and the angle to the road surface verticals. The Doppler laser L_{ref} (reference laser), which measures the area in front of the measuring system which has not been disturbed by the introduction of load, is used as a reference for compensating for the vertical vehicle dynamics and twisting of the measuring beam. The reading that enters the calculation is therefore not the actual angle for the Doppler laser, but rather the (constant) angle difference compared to the reference laser.

The so-called slope value (gradient of the deflection at this sensor position) is formed for each sensor position i using the corrected vertical velocity vector $V_{v\,i}$ and the horizontal driving velocity relating to the measurement vehicle V_h as follows: $Slope_i = S_i = (V_{v,i})/V_h$.

The principle of calculating the slope value is shown in Figures 1 and 2.



U = Doppler laser (sensor) at position i
Vv, i = Corrected velocity with which the carriageway beneath the vehicle moves in a vertical direction
Vh = Velocity with which the carriageway beneath the vehicle moves backwards
Si = Slope (gradient of the road surface) at position i

Figure 1: Schematic diagram for calculating the slope value in a vehicle-based coordinate system (not shown to scale)

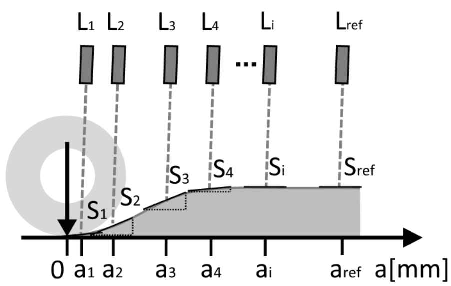


Figure 2: Arrangement of the Doppler lasers to calculate the slope values (not shown to scale)

2.2 Description of the measurement vehicle

2.2.1 General remarks

Figure 3 shows an example of a measurement vehicle:

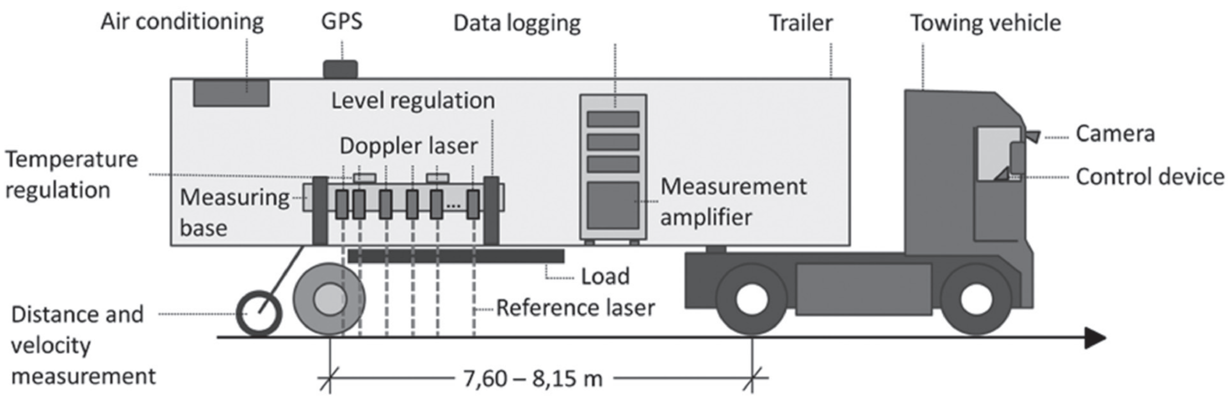


Figure 3: Schematic diagram (section) of the measurement vehicle

The measurement system consists of a towing vehicle and a single axle semi-trailer. The details of the equipment currently used are as follows:

- Dimensions: length of the semi-trailer between kingpin and axle: 7.60 m – 8.15 m,
- Load axis (axle) of the semi-trailer:
  - Dual tyred (tyres e.g. 315/80 R 22.5 or 275/70 R 22.5);
  - Standard axle load 10 t.

The axle load can be varied by loading or unloading weights. Chapter 3.1.1 must be noted if the axle load is increased such that it exceeds levels generally permitted under Section 34 of the Straßenverkehrs-Zulassungs-Ordnung – StVZO (German Road Traffic Licensing Regulations).

2.2.2 Requirements placed on the measuring equipment

A measuring beam which the Doppler lasers are attached to is installed in the semi-trailer. The measuring beam must be extremely rigid and resistant to distortion in order to guarantee a constant alignment of all Doppler lasers. For this reason, the measuring beam and the inside of the semi-trailer must also be kept at a constant temperature to minimise temperature-related bending.

The quantity of Doppler lasers depends on the measuring task. Currently between 5 and 10 Doppler lasers are used, of which one is used as reference laser and attached as far as possible from the semi-trailer axis which causes the deflection (currently 3. 50 m).

The measuring beam must be guided as evenly as possible over the measurement surface to maintain the specific measurement range of the Doppler lasers. The measurement principle is only slightly affected by relative movements. These are compensated for arithmetically using the reference sensor data and the acceleration sensors and gyrometer.

The results are currently usually displayed in 10 m readings, however an analysis with shorter grid lengths may be useful when considering certain issues.

2.2.3 Recording the axle load

Measuring systems with dynamic axle load recording are suitable for the documenting and possible consideration of the dynamic influences that are induced by unevenness and introduced into the asphalt pavement by axle load.

2.2.4 Recording the travel speed

Precise information about the driving velocity is needed to calculate the deflection. A separate measuring wheel, for example, is useful when recording this.

2.2.5 Recording the measuring path and coordinates

The measurement data (deflection velocities, temperatures, images etc.) must be referenced with accurate information about the path and coordinates for subsequent evaluation and interpretation. A sufficiently accurate odometer and a global navigation satellite system with inertial measurement system (e.g. GPS) are, for example, suitable for localising data.

2.2.6 Pictorial documentation

Pictorial documentation is helpful when interpreting data. Continuous photos can be taken of the route, e.g. every 10 metres, and it has proven useful to link the images with measurement data in such a way that the respective measurement point is illustrated at a firmly defined point in the image.

2.2.7 Recording temperatures

The air temperature in the semi-trailer and the temperature of the measuring beam must be documented throughout to check plausibility and for quality assurance. It is particularly important to record the temperatures of the top and underneath of the measuring beam with sufficient accuracy, as these are relevant to deflection.

Furthermore the outdoor air and surface temperatures of the road surface must be recorded continuously. The surface temperature can be measured using a pyrometer (e.g. infrared measurement sensors). The outdoor air temperature must be measured uninfluenced by the measurement vehicle. The temperatures must be recorded to an accuracy of ± 1 °C. Among other things, they may be used to correct or check the plausibility of the measurement results.

2.3 Application limits of data collection and evaluation

The usual geometric and weight-related limits and legal provisions (e.g. for tight bends, bridges and traffic prohibitions) apply to the measurement vehicle.

When selecting the measurement speeds, the viscoelastic properties of the asphalt must be taken into consideration. Comparable results are to be expected in a speed range of more than 40 km/h.

Temperature limits for the core temperature of the asphalt must also be considered for the measurement because of the temperature-related deflection properties of the bound asphalt layers. TSD measurements on asphalt road pavements should therefore only be conducted at pavement temperatures of between ≥ 5 and ≤ 30 °C. The surface temperature to be recorded during measurement may alternatively be used to estimate the pavement temperature. The unbound layers and the subgrade/road bed must not be frozen during measurements. If it is to be assumed that measurements will be conducted during the frost or spring thaw period, this must be documented.

The measurements are not valid in tight bends because the geometric measurement conditions (all Doppler lasers must record the measurement object in a single measurement line) cannot be complied with here.

Deflection measurements using Doppler lasers require a consistently reflecting road surface. Wet conditions, clouds of dust and other coarse contamination (e.g. leaves) impair the reflective properties and thus the measurement. This can usually be recognised by a change in the data rate of the Doppler lasers.

Very small deflections that cannot yet be reliably recorded by the TSD occur on very rigid asphalt road pavements or when driving over concrete structures.

Great longitudinal unevenness such as potholes, individual obstructions etc. may locally impair the measurement result.

3 Measurement

3.1 Preparation

3.1.1 Special permission

The standard axle load during measurement is 10 t. In exceptional cases it may be useful to increase or reduce this load. The maximum possible axle load of the TSD of 13 t may exceed the maximum axle load of 10 t permitted for a non-powered single axle in accordance with Section 34 of the StVZO. In these cases it is essential to obtain special permission for the vehicle in accordance with Section 70 StVZO. An additional permit under Section 29 (3) StVO (excessive road use) is then not necessary where the vehicle is viewed by the competent authority to be providing a service for the construction and maintenance of roads. It is then exempted under Section 35 (6) StVO (special privileges for vehicles serving the construction and maintenance of roads) from observing the provisions of the StVO and therefore also Section 29 (3) StVO). It is necessary to comply with the provision under Section 35 (8) StVO (consideration of public safety and order) when taking advantage of the special privilege.

3.1.2 Securing the measurement vehicle

The measurement vehicle must be marked according to relevant regulations (including DIN 30710) and secured. During measurement trips on motorways or multiple lane dual carriageways, it is necessary to heed the *Hinweise zur Sicherung von Messfahrzeugen für die Zustandserfassung und -bewertung auf Bundesautobahnen und Bundesstraßen mit mehreren Fahrstreifen pro Richtung* (Notes for securing measurement vehicles for assessing and evaluating the condition of national motorways and federal highways with multiple lanes per direction) (HSM 2000).

3.1.3 Specification of the lane and the measurement line

On roads with more than one lane, measurements should be conducted on the right-hand/nearside wheel path of the lane most used by heavy goods traffic. This is generally the right-hand lane in each direction of travel. It is also possible to measure other lanes or measurement lines, however, to address specific issues. In this way the comparison of structural stability between lanes with most heavy goods traffic and the other lanes can produce additional findings. As the measurement equipment is firmly located in the right-hand wheel path of the measurement vehicle, special considerations, e.g. also regarding securing the traffic, are required in the case of other measurement lines.

If the heavy goods traffic load ($DTV^{(SV)}$) in both directions varies greatly and/or there are differences in design (method of construction, layer thicknesses, material changes, subgrade conditions), then both directions of travel must be incorporated in measurements.

3.1.4 Specification of the measurement speed

It is advisable to specify guide speeds for data collection. These should be selected according to the road to be recorded, its degree of development and lines or the permitted speeds (e.g. roads through towns, open stretches of road). To permit results to be compared at a later date, the aim should be to record deflections at the most even, uniform speed possible (ideally between 40 and 80 km/h).

3.2 Execution

Before each measurement, it is recommended that a visual inspection be made of the equipment and relevant recording systems (Doppler lasers, temperature probes, cameras, distance meters, safety equipment, air conditioning).

Data collection should not begin right at the start of the section to be recorded or stopped at the end, but rather allowing an appropriate approach and slowing down (recommended to be at least 50 m). This enables the operational readiness to be established and any necessary corrections to be made regarding the start and end point.

Before starting the measurement, the distance and speed measuring wheel should be lowered onto the surface of the asphalt road pavement.

The recording of the deflection generally starts in the middle of the right-hand/nearside wheel path (see Chapter 3.1.3). The vehicle should be guided accordingly. If the wheel path is not visible, a track position should be selected that is typically used by a truck. Any moving away from the measurement line (e.g. because of obstructions) must be indicated in the data through the use of markings (e.g. event markers).

Clipping the edges of defined wheel paths must be avoided. Areas with very tight bends must be indicated in the data and excluded from the assessment, because it is not possible to fulfil the geometric measurement conditions here.

It is necessary to keep to the abovementioned guide speeds where the situation regarding traffic and traffic law so permits. Lateral acceleration in tight bends should be limited where possible by adapting driving style. Abrupt braking or acceleration should be avoided wherever possible.

During the measurement, the functional efficiency of the system must be monitored. The data rate obtained by the Doppler lasers may be taken into consideration here and in the interpretation as quality criterion. It may usually be viewed to be critical if the data rate falls below half the possible data rate. The images taken of the route during the measurement should be inspected to clarify causes. If the data rate of one Doppler laser deviates significantly from the others, a malfunction of this laser may be assumed.

Records must be kept of all measurements together with file names and any relevant information (weather, special features etc.).

3.3 Quality assurance

Quality assurance is a process that must be conducted painstakingly and continuously. It should be multi-level, and in addition to routine inspections of the operating principle of the measurement system (see Chapter 3.2) before, during and after measurement, should also encompass regular self-monitoring or third party monitoring and fundamental calibrations of the main measurement systems (Doppler lasers, reference lasers, gyrometer, temperature probes) at greater intervals or as required.

As the TSD involves a dynamic and technically complex measurement method which cannot be calibrated and inspected using simple tests when in standby mode, operators of the equipment must conduct regular monitoring themselves. This enables undesired changes to be detected and rectified in good time. To this end, repeat measurements should be conducted on familiar sections of routes at shorter intervals (e.g. every two weeks or before and after measurements), evaluated and clearly documented. The self-monitored routes should be at least 2 km long and have different levels of structural stability (high, medium, weak).

It is furthermore advisable for the client to have the collected data checked on a random basis by means of third party monitoring using a second, independent measuring instrument.

There are not yet any recognised requirements regarding self-monitoring or third party monitoring of the TSD, however they are the subject of research projects and studies by relevant specialist groups.

Likewise there are no binding requirements to date for calibration of the TSD. The current view is that calibration should be conducted at longer intervals (e.g. during an annual inspection) and should incorporate the following checks:

- Calibration of the individual Doppler lasers in dismantled state in a suitable test facility.
- Calibration of the relative alignment of the Doppler lasers to each other. In addition to measuring the alignment, dynamic measurements must be taken on a surface that is (almost) free from deflection.
- Plausibility check of the structural stability measurements or the entire system on a measurement route with familiar properties and of sufficient length or running over a test route with sensors to record vertical velocity/vertical acceleration.
- Comparative measurements with a second TSD vehicle.
- Calibration of the measuring beam with installed Doppler lasers, acceleration sensors and gyroscopes in a suitable test facility.
- Calibration of the temperature probes using a temperature controlled water bath.
- Calibration of the distance measuring wheel on a previously measured route of sufficient length.

- Functional check of the air conditioning on the measuring equipment, including plausibility check of the temperature measuring equipment.
- Functional check of the inertial measuring system/global navigation satellite system receiver.
- Functional check of the mechanical components of the measuring equipment.

The results of calibrations should be clearly documented.

3.4 Results, data formats

The collection results directly in raw measurement data and route images. These data contain the detailed, fundamental output variables for the different laser sensors and data logging equipment. In familiar systems, they are provided in a binary format, which means they are not readable without further description.

Using the software provided by the manufacturer, the extremely high resolution raw measurement data are processed, aggregated to prescribed grid lengths and read out as “base values” for the device in the form of a readable text format. This processing of the raw data to base values also takes account of any system and calibration constants. It should be possible to physically interpret the base values (e.g. speeds as base values of the Doppler lasers).

In addition to general specifications on measurement and the selected evaluation parameters, the data collected include the linear metres of measurement, geo coordinates, event markers and the name of the corresponding route images which may subsequently be used to localise the results.

Further measurement results can be calculated using the base values (e.g. slope or deflection). These further measurement results simplify evaluation because as a rule they describe the measurement object more meaningfully than the base values.

3.4.1 Evaluation and assessment

Different methods can be used to interpret the base values and other measurement results (essentially the slope values). Possible standards for evaluation and assessment will be presented in AP Trag (working paper on bearing capacity), Part C 5.

Traditional methods for evaluating measurement data from the TSD in principle are listed in the Annex.

3.4.2 Presentation of the results

As things currently stand, most base values and other measurement results for the TSD are entered into an (electronic) spreadsheet in which one row is assigned to each measurement section and one column to each base value/other measurement result. This spreadsheet contains information about the longitudinal profile recorded, the degree of unevenness IRI calculated using this, the driving velocity, temperatures (road surface, inside and outside air temperature, measuring beam), the dynamic axle load, the Doppler velocities of the individual lasers, the vertical velocities calculated from this using the algorithm developed by the device manufacturer on the basis of the functional approach, the slope values and the deflections. Currently, manufacturers and users are working on advancing the method of evaluating measurement data using the various approaches set out in the Annex.

For data exchange and for further processing of the measurement data, transformation into an XML geo raw data format which can be evaluated using the standard programs of the Federal Highway Research Institute (BASt) in the same way as road monitoring and assessment (ZEB) is recommended to achieve the reliable and simplified allocation of data to the road network. Initial applications have already been successfully realised. With these, localisation information (road, section, station) that is compliant with ASB (road knowledge base instructions) can be entered using an automated process into the data stream and then used for subsequent evaluation or presentation.

4 Bibliography and standards, ordinances

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2 Pedersen, L: Viscoelastic Modelling of Road Deflections for use with the Traffic Speed Deflectometer; Technical University of Denmark and Ministry of Science and Innovation, Denmark, 2013

3 Ferne, B; Fairclough, R.: Development of the UK Highways Agency Traffic Speed Deflectometer. In: The 8th International Conference on the Bearing Capacity for Roads, Railways and Airfields, Illinois, 2009

4 Weller, O.; Degelmann, R.; Jansen, D.; Tragfähigkeitsmessungen mit dem Traffic Speed Deflectometer (TSD). In: Straße und Autobahn 2014, H. 11, P. 870–879

Standards and ordinances

DIN 1)	30710	Safety marking of vehicles and equipment
FGSV 2)	AP Trag	Working papers on the structural stability of asphalt road pavements – Part C 5: Standards for evaluating and assessing measurement results (in preparation)
VkBl. 3)	HSM	Hinweise zur Sicherung von Messfahrzeugen für die Zustandserfassung und -bewertung auf Bundesautobahnen und Bundesstraßen mit mehreren Fahrstreifen pro Richtung, Notes for securing measurement vehicles for assessing and evaluating the condition on national motorways and federal highways with multiple lanes per direction published in VkBl. 2000, H 16, Pages 512–515
BASt 4)	ASB	Anweisung Straßeninformationsbank (road knowledge base instructions)
BGBl. 5)	StVZO	Straßenverkehrs-Zulassung-Ordnung (Road Traffic Licensing Regulations) (FGSV R 130)
	StVO	Straßenverkehrs-Ordnung (Road Traffic Act) (FGSV R 129)

Sources of references

1) **Beuth Verlag GmbH**
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Email: info@beuth.de, Internet: www.beuth.de

2) **FGSV Verlag GmbH**
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Email: info@fgsv-verlag.de, Internet: www.fgsv-verlag.de

3) **Verkehrsblatt-Verlag (Transport Gazette)**
Address: Schleefstraße 14, 44287 Dortmund
Tel.: 02 31/12 8047, Fax: 02 31/128009
Email: info@verkehrsblatt.de, Internet: www.verkehrsblatt.de

4) **BASt – Bundesanstalt für Straßenwesen (Federal Highway Research Institute)**
Internet: www.bast.de (>Verkehrstechnik>Publikationen>Regelwerke zum Download> Anweisung Straßeninformationsbank – ASB)

5) **Bundesgesetzblatt (Federal Law Gazette)**
Internet: www.gesetze-im-internet.de
and included in the FGSV Reader, premium version, module “Alles was Recht ist”

All FGSV publications listed are also available in digital form for the FGSV Reader and included in the comprehensive subscription service “FGSV – Technische Regelwerke – Digital”

Annex

Additional explanation of the method and the evaluation and assessment of the measurement

As explained in Chapter 2.1, the slope of the deflected asphalt road pavement is determined at the individual sensor positions (slope values). The deflection curve can be derived from this. This may be undertaken using various methods which differ in terms of accuracy and expense:

- Geometric approach: the deflection curve is reconstructed using the existing slope values.
- Function-based approach: the form of deflection curve is prescribed by a mathematical model equation. This is solved using the actual measurements.
- Fitting method: parameters for various scenarios are determined mathematically using analytical and empirical methods, e.g. finite element methods). These are compared with the metrological variables achieved to identify the best possible match.

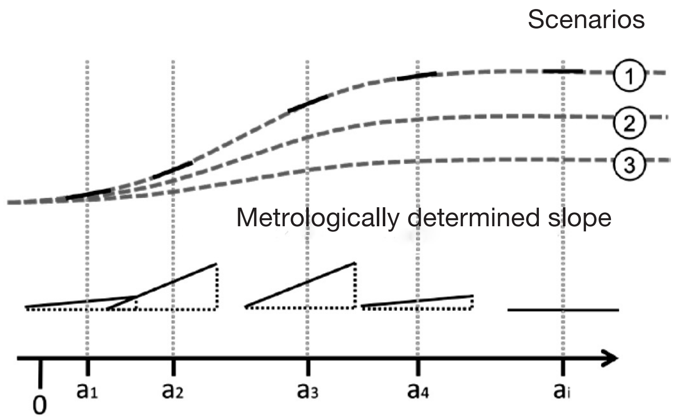

Image A1: Schematic diagram for the approach using the fitting method

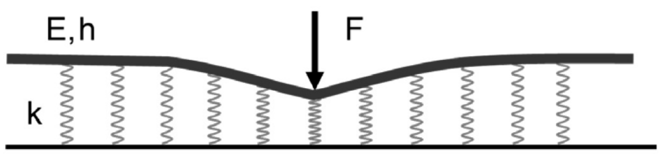

Image A2: Schematic diagram of the Winkler equation

The approach currently used by the manufacturer of the TSD is a function-based approach and uses the elastic bedding beams familiar from statics ("Winkler bedding model", refer also to Image A 2). Using the slope values calculated, it is possible to determine the constants of the Winkler bedding model, and then calculate the deflections for the specific location. All parameters required for the evaluation and familiar from other structural stability measurement systems can be determined from this.

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R stands for regulations:

These publications either specify the technical design or realization (R1) or give recommendations on the technical design or realization (R2).

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