Using traffic speed deflectometer to measure deflections and evaluate bearing capacity of asphalt road pavements at network level

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Abstract. The paper deals with diagnostics of bearing capacity of asphalt pavements by a Traffic Speed Deflectometer (TSD device), which allows to measure pavement deflections continually at the traffic speed on the basis of dynamic loading induced by moving wheel of a reference axle at the speed of up to 80 km/h. The paper aims to inform of a new method to measure road pavement deflections, describes the principles of measuring pavement deflections by TSD device, and presents results of comparative measurements between FWD (Falling Weight Deflectometer) and TSD devices organized by CDV in Italy and Slovakia. Particular attention was paid to the difference between deflections measured by FWD and TSD devices.

1. Introduction

The diagnostics of asphalt pavements in terms of their bearing capacity is usually performed by the measurements of pavement deflection by a Falling Weight Deflectometer (FWD), which applies loading on the pavement by a stationary impulse. FWD allows to set the loading parameters so that they would be similar to real loading by wheels of moving vehicles. However, the real deflection corresponds the most with the deflection measured during dynamic loading (movement of vehicles).

Traffic Speed Deflectometer (TSD) is the latest device meeting this criterion, which is an alternative to pavement deflection measurement by FWD. The advantage of a TSD is continuous measurement of deflections of the whole diagnosed road segment, which is not limited to measuring of selected points as in the case of an FWD. The deflections measured by a TSD are evaluated in 10-metre intervals.

Contactless measurements at the speed of up to 80 km/h have no restraints to road traffic and the measurement capacity considerably increases in comparison to a FWD. Thanks to this, a TSD device allows fast and safe data recording and is a suitable device for diagnostics at the network level (evaluation of the whole network under the management of a relevant administrator in order to evaluate and identify the weakest road sections).

There are currently 8 of these devices in operation in the world. In Europe there are devices in Denmark (DRD, GE A/S), Italy (ANAS S.p.A.), Poland (IBDiM) and Great Britain (TRL). In order to verify a correlation between FWD and TSD data, comparative measurements are performed for both devices and pilot projects are established for the integration of TSD into the pavement management system.
Traffic Speed Deflectometer, methodology of measurement, analysis and evaluation of measured data are more and more advanced.

2. Traffic Speed Deflectometer
Traffic Speed Deflectometer measures bearing capacity of roads contactlessly at the speed of traffic flow. The road deflection is measured under dynamic loading induced by rolling vehicle wheels, which is most similar to the real deflection induced by loading of heavy vehicles (magnitude, duration).

Based on the recorded deflection values, the user receives complete data on road pavement bearing capacity along the whole measured road section. In contrast to diagnostics with FWD, the issue with road traffic restraints is avoided, safety of road users as well as of measuring vehicle crew during the measurement is higher. Another advantage is high measurement capacity, which allows to measure up to several hundred kilometers of roads per day (approx. 350 – 450 km on average). According to the information from IBDiM organization, daily measurements of more than 800 km are no exceptions. The measurements cannot be performed in rain or on wet road pavements due to the use of laser sensors.

The system consists of a heavy vehicle with a truck and a modified semitrailer (Figure 1). The single axle semitrailer contains a measuring system for measuring road pavement response to loading. The standard loading per axle is 10, or 12 tonnes respectively. Therefore, corresponding weight is installed under the semitrailer container. The main part of the measuring system is a rigid beam with appropriate number of Doppler laser sensors (Figure 2), which scan the road pavement of the right wheel path in the axis (dual tires), and other parts include support and computing systems. The number of laser sensors ranges between 6 and 10.

The crew of the TSD system consists of a vehicle driver and an operator, who controls the measurement and the recording of data during the measurement.

3. Principle of TSD deflection measurement
The loading applied to the pavement by a rolling TSD wheel causes deformation of road pavement (deflection basin). Road pavement deflection velocity is measured with the use of Doppler laser sensors, which are fixed to a rigid beam in a corresponding distance from the loading position. Subsequently, the deflection velocity is used for a calculation of the road pavement deflection. The emitted laser beam is reflected by the road pavement and the sensor measures the speed of short-term vertical deformation of the loaded road pavement along the direction of the laser beam.

Since the sensor is not placed exactly perpendicular to the road pavement, the laser beam falls at the angle of approx. 2°. Apart from the required pavement deformation velocity $V_\psi$, the Doppler-laser
sensor registers vehicle speed $V_{VH}$. Relatively low angle allows the input of vehicle speed into the calculation and also has only marginal effect on the vertical composition of deformation velocity.

A deflection slope (tangent) [µm/m] is calculated with the use of simultaneously measured vehicle speed and the defined laser beam angle towards the vertical axis. Deflection slope is calculated as the ratio $V_V / V_{H}$ [5].

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Slope = \frac{V_V}{V_{H}}
\]

**Figure 3.** Calculation of slope of deflection bowl. [4]

Figure 4 (left) shows the pavement deflection velocity vectors under a rolling wheel. Together with deflection velocity, the corresponding deflection basin is shown in Figure 4 (right), where deflection slopes (tangents) are displayed.

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SCI_{300} = \int_{0}^{300} s(x) dx = d_{300} - d_0
\]

Where $s(x) = \text{slope at location } x$, $d(x) = \text{deflection at location } x$.

The lowest possible step for the export of the measured data by a TSD is 10 metres. This boundary value is given by software used for further processing of measured values, which was developed by Greenwood Engineering A/S. It is possible to evaluate data for a distance lower than 10 metres, but without the values of calculated deflections. When calculating deflections at constant distances, the
representative deflection value for each distance is calculated with the use of statistical methods, which are parts of the software.

4. Comparative measurement between TSD and FWD
Comparative measurements between TSD and FWD devices were performed in 2014 and 2015 within the project of the Technological Agency of the Czech Republic No. TE01020168 (CESTI).

In November 2014 near Rome, a comparative measurement was performed with an Italian TSD in the ownership of a research institution ANAS S.p.A. – Centro Sperimentale Stradale and an FWD RODOS 2012 of Czech production, whose owner is a research institute Centrum dopravního výzkumu, v. v. i. The measurements was performed on several road segments with asphalt pavement. One of them was SS1 (Strada Stanale 1 Via Aurelia) with the length of the measured segment of 3 km. The TSD measured road pavement deflections at the speed of 60-80 km/h, depending on traffic flow speed. The measurement step of the FWD device was 20 m. After excluding erroneous data, more than 150 deflection curves were measured. The export of data from the TSD was performed in the same measurement step, i.e. 20 m.

A comparative measurement of an FWD and a TSD, owned by a Polish research institute IBDiM, was performed on 3 road sections with asphalt pavement on D1 (2.5 km), I/18 (1.95 km), II/537 (2.5 km) near Liptovský Mikuláš in Slovakia in June 2015.

Deflections on roads I/18 and II/537 were measured by the TSD at the speed of approx. 70 km/h. In addition, deflections on motorway D1 were measured at different speeds of the TSD (approx. 60 km/h, 70 km/h, 80 km/h). The measurement step of FWD device was 25 m on all measured road segments. After excluding all erroneous data more than 250 deflection curves were measured. The export of data from the TSD was performed in the same measurement step, i.e. 25 metres.

5. TSD and FWD measurement result evaluation
Comparative measurements between FWD and TSD devices which were performed on road segments described in the previous chapter were evaluated in order to find a correlation between deflections from both devices.

Deflection values after corrections for loading force and temperatures were used for the correlation. The deflections measured by FWD and TSD devices were corrected to the comparative force of 60 kN (Italian TSD has loading 12 tonnes per axle), or 50 kN respectively (Polish TSD has loading 10 tonnes per axle). The calculation used in Italy [1, 2], or in Slovakia [6] respectively, were used for the temperature correction. Temperature correction had no considerable effect, since the measurements of FWD and TSD devices were performed in the same temperature conditions.

The degree of correlation between the deflection values measured by a TSD and FWD in Slovakia was determined with the use of linear regression, and the correlation reliability was expressed by reliability coefficient $R^2$. The results of the determination of deflections correlation in the loading position for linear relationships are shown in Table 1.

Regarding the differences in the method of road pavement loading, the loading time in subgrade and subbase layers is different for TSD and FWD measurements. The loading time of asphalt road layers is relatively comparable. Evaluation of asphalt layers uses the index SCI$_{300}$ (according to [3] a difference of deflections measured in the loading position and at the sensor located 300 mm from the loading position). Therefore, in the next phase the correlation of index SCI$_{300}$, mentioned in the TSD results and calculated from FWD outputs, was examined. Similarly to the deflection on the loading position, the relationship between the values of indexes SCI$_{300}$ were examined with the use of linear regression and coefficient of determination $R^2$. The results for the linear relationship are shown in Table 1.
Table 1. Comparison of TSD – FWD in Slovakia; coefficient of determination $R^2$.

| Parameter | d0       | SC1300  |
|-----------|----------|---------|
| TSD speed | 60 km/h  | 70 km/h | 80 km/h | 60 km/h | 70 km/h | 80 km/h |
| Measured  |          |         |         |         |         |         |
| segment   |          |         |         |         |         |         |
| D1        | 0.36507  | 0.36262 | 0.24755 | 0.05428 | 0.16924 | 0.10794 |
| 1/18      | -        | 0.03098 | -       | -       | 0.09329 | -       |
| II/537    | -        | 0.10451 | -       | -       | 0.06227 | -       |

The values of coefficients $R^2$ in Table 1 are relatively low. According to the criteria of determining the relationship of two variables on the basis of the reliability coefficient and regarding the values in the range of 0.1 to 0.25, the relationship is weak. The range from 0.25 to 0.5 characterizes moderate relationship strength, 0.5 to 0.8 shows strong relationship and over 0.8 it is very strong relationship of two variables. Therefore, there was a weak relationship between the values of deflections measured by TSD and FWD devices. Very weak relationship was found for the parameter SC1300 in this case. In contrast, the results of measurements from Italy showed similar shape of curves comparing parameters SC1300 (Figure 5). When evaluating the results obtained in Slovakia, a problem occurred with the accuracy of localization of both devices. This was probably the reasons for weak relationship of both devices. The localization accuracy during the measurement has the same importance as correct deflection data from the measurement.

Figure 5. Comparison of index SC1300 on road SS1 (Italy).

Regarding the deflection trends, the evaluations of results (SCI300 and D0) from Italy found the same trends, i.e. the increase in FWD values correlated with the increase in TSD values (Figures 5, 6). This means that if TSD was able to identify differences in bearing capacity of individual road sections. This is important for the usability of TSD for the diagnostics of bearing capacity at the network level.
6. Conclusions

Based on the evaluation of measurement results by TSD and their comparison with the measurement results by FWD, more conclusions can be made in terms of the usability of TSD device for the diagnostics of bearing capacity of asphalt road pavements at the network level.

First of all, TSD is a high performance device, which is able to diagnose a large length of the road network within a short time.

Another advantage is diagnostics at the speed similar to the real road traffic flow speed, while safety protection measures for the measurement vehicle and its crew are unnecessary. In comparison with FWD diagnostics, it is a crucial advantage in terms of traffic safety. Apart from that, the diagnostics outcomes more correspond with the real loading conditions, since they contain dynamic aspects based on the road pavement longitudinal unevenness. Furthermore, the loading time in individual levels (layers) of road structure corresponds with the real loading.

The extent of information from TSD measurements is sufficiently large. It includes all other important input data used for standard evaluation of road pavement bearing capacity. The outcomes not only include the deflection in the position of loading axle and different (standardly used) distances from this position, but also values of different indexes calculated from the mentioned deflections.

Based on the evaluation of performed comparative measurements, the same trend in deflections of TSD and FWD was found. This is important in terms of the usability of TSD device for diagnostics at the network level.

Regarding the evaluation criteria, existence of the relationship between TSD and FWD devices was found, although the relationship differed for individual testing trials. Therefore, we may deduce that it is possible to use the evaluation criteria for road pavement bearing capacity from FWD measurements to derive the evaluation criteria on the basis of TSD measurement results. It is necessary to perform more extensive measurements to collect a larger statistical file of measured data (roads of different classes and constructions, with different thickness of layers and different bearing capacity), and design a system of road pavement bearing capacity evaluation at the network level on the basis of TSD measurements.

The comparative measurements showed the importance of correct localization of measured data. Nowadays, localization is not only performed through the driven distance, but also with the use of GPS coordinates and combination of other systems (IMU, image recording). In addition, it is useful to have reference points on the road with known coordinates, where the localization accuracy can be verified. The measurement localization accuracy at higher speeds is as crucial as the correct deflection data.
A relatively small statistical file of measured data collected from the measurements in Italy and Slovakia may have caused low reliability of results. Therefore, a pilot project with the aim to collect larger amount of TSD data for the evaluation at the network level was performed at the end of 2016 in the Czech Republic. This project was funded by the State Fund for Transport Infrastructure (No. 5006210261). The TSD device measured in total 170 km asphalt road pavements of different classes and constructions in South Moravian region. The selected road sections were also measured by an FWD device. A detailed analysis is currently underway for the results of both methods in order to find differences between the methods and for evaluating potential application of a TSD device in the Czech Republic. The final results of this project was unavailable when this article was written.

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