Chinese Society of Pavement Engineering
International Journal of
Pavement Research and Technology
Journal homepage: www.springer.com/42947

# Incorporating truck speed effect on evaluation and design of flexible pavement systems

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Received 9 July 2019; received in revised form 8 September 2019; accepted 1 October 2019

**Abstract**

The ever increasing traffic volumes and density on road network worldwide coupled with accelerated deterioration of road conditions continuously motivate pavement engineers to seek improvements to existing pavement analysis and design methods. Most current pavement analysis and design procedures either assume static loading or perform quasi-dynamic analysis by characterizing asphalt materials using loading frequency on specimen to get complex moduli for input into response models. Correct simulation of pavement response to dynamic loading is critical to mechanistic analysis of pavement systems.

The present study used a Traffic Speed Deflectometer (TSD) to induce the dynamic loading to the flexible pavement systems at predetermined speeds and wander. Elastic surface deflections from eight different flexible pavement sections were measured using the Multi-Depth Deflectometer (MDD).

The study investigated and proposed a methodology for normalising deflections measured at different moving load speeds using Speed Adjustment Factors (SAFs). The SAFs showed that the influence of speed on the pavement response to dynamic loading varied significantly depending on the type of the flexible pavement systems.

Keywords: Elastic surface deflection; Speed adjustment factor; Dynamic loading; Flexible pavement systems

## 1. Introduction

The road network in South Africa and worldwide, particularly in urban areas, is experiencing steady increases in traffic volume and density. High traffic density at slow operational speeds leads to traffic congestion. Traffic speed has a significant effect on the response of flexible pavement systems to loading. Traffic loading is one of the major determinant factors to deterioration and failure of pavement systems. It follows that traffic loading is one of the important input parameters in mechanistic-empirical pavement design methods. Mechanistic-Empirical (ME) pavement design methods apply elastic theories to calculate the stresses and strains in pavement layers under a given traffic wheel loading (pavement response to loading) and use empirical relationships (transfer functions) to determine the number of load repetitions to failure (distress prediction) [1].

The ME based flexible pavement design procedures have evolved over the past decades [2-6]. Pavement engineers and researchers have over-time developed better understanding of pavement materials behaviour and its interaction in pavement systems. In the recent decades, simulation of traffic loading has advanced from looking at it as static and quasi-static to dynamic loading. Dynamic loading is time dependent and considers mass inertia and damping forces effect on pavement responses due to a moving load.

Therefore, mechanistic response data from instrumented, full-scale test road facilities are essential for the validation and further development of the ME models. The South African Road Agency (SANRAL) constructed an instrumented experimental section on Road 104 in Pretoria east with a variety of sensors to capture amongst other things the flexible pavements mechanistic responses to dynamic traffic loading.

The objective of the present study was to investigate the application of effect of truck speed through Speed Adjustment Factors (SAFs) in pavement evaluation and design procedure. Methodology for normalising deflections conducted at different speeds and equipment. Forward application of the SAFs in sensitivity analysis of different pavement rehabilitation options to change in operational speeds was proposed.

### 1.1. Modelling traffic loading

Traffic loading ,as an input into ME method, can be considered as a static loading, quasi-static loading or a dynamic loading. Earlier pavement analysis procedures considered traffic loading as

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Peer review under responsibility of Chinese Society of Pavement Engineering.

ISSN: 1996-6814 DOI: https://doi.org/10.1007/s42947-019-0085-1
Chinese Society of Pavement Engineering. Production and hosting by Springer Nature

static load owing to limitations in the models and computation power. Use of static load only simulate a stationery truck loading where as a load moving at very slow speed can be analysed as a quasi-static loads. It is assumed that at very slow speeds, strain rate is very slow and inertia force is negligible.

In quasi-static analysis, the fundamental assumption is that the loading is applied so slowly (very low frequency when compared to that of the structure) that basically the structure deforms in a static manner and inertia effects can be neglected. This assumption works well when inertial effects are very low and it helps simplify the non-linear problems to a linear system. However, this is not the case in a dynamic analysis where inertia forces are not small enough to be neglected. Inertial forces result from Newton's second law ($F = MA$). So in a dynamic analysis, acceleration is taken into account.

Recent research has shown that truck speed has significant effect on response of flexible pavement systems to moving load [7-13]. To date speed effect is incorporated into materials characterisation through cyclic loading of specimen for determination of complex modulus [ $|E^*|$] of asphalt materials. Traffic loading of pavement systems is considered in the form of the loading pulse time ( time that the tyre patch is in contact with the pavement surfacing) and gap time between successive tyre patches. Al-Quadi et al. [7] explains how this load pulse time is converted into load frequency and used as input into the loading simulation of asphalt in laboratory tests and its application in asphalt mix design [14]. Different loading frequencies of cyclic loading are thus used to simulate different operating speeds.

A vehicular dynamic load causes a structure to vibrate and the inertia force is big enough not to be neglected, and therefore the dynamic loading forces are represented by the following equation;

$$F = Ma + cv + Kx = M\frac{d^2x}{dt} + c\frac{dx}{dt} + Kx \quad (1)$$

where, $M$ is the mass of the axle, a is acceleration , $c$ is the damping coefficient (resistance of the pavement to oscillation), $v$ is velocity of the mass, $K$ is the stiffness of pavement, and $x$ is elastic displacement of the pavement.

### *1.2. Influence of speed of moving load on pavement systems response*

In the early days of pavement engineering, researchers considered a moving wheel load in the form of duration of loading (or frequency or rate of loading). In the early days of pavement engineering, simulation of field conditions and in-situ testing of pavement response was considered very complex and expensive and hence engineers relied on testing samples of materials in the laboratory with the hope that the tests simulated the in situ conditions [15]. At the time, the work of Van der Poel [16] presented the best approach to determination of stiffness of bitumen layers under given loading time or frequency, temperature difference and penetration index of the bitumen.

Multi-Layered Elastic Theory (MLET) is employed to calculate the responses of layered systems under concentrated or distributed loading [2,17]. Appropriate characterisation of different pavement materials is essential in formulating a pavement system response model. Input of correct stiffness modulus of pavement layers is central to generating appropriate pavement response values at critical locations in the pavement structure. Influence of truck speed on stiffness modulus of pavement materials is there for essential. Considering that it is difficult to measure stress and strain in the existing pavement structures that has live traffic flow, pavement engineers use deflection measuring equipment to capture the pavement response. This deflection is used in back-calculation process to determine stiffness modulus of pavement layers. Several researchers have shown that speed of moving load has significant effect of pavement response (stress, strains and deflection) values. Most of the current deflection measurements, processing of deflection data and back calculation procedures do not take into account the effect of speed.

De Beer [8] investigated pavement response to moving loads (5 to 80 km/hr) by measuring pavement deflections using the Multi-depth Deflectometer (MDD) and strain gauges. The study focused on heavy duty pavement structures comprising 50 to70 mm asphalt surfacing placed on crushed stone base, cemented base and asphalt base. The study showed the relative effect of pavement temperature and vehicle speed on pavement response. It was concluded that pavement structural life was not a constant, but varies according to temperature and speed of moving load effects, depending on the type of pavement structure. The study recommended further investigation in the effect of vehicle speed and dynamic characteristics (damping and inertia) on pavement systems response.

Synthesis by Gillespie et al. [9] also reported amongst many significant findings that vehicle speed affected primary response of flexible pavements through the load duration. It was argued that increase in dynamic loads with speed is compensated for by the shorter duration of an applied axle load at increased speed.

Sebaaly and Tabatabaee [10] investigated the influence of vehicle speed on dynamic loads and pavement response using Weigh-In-Motion (WIM) technology. Pavement strains under moving vehicles were measured using strain gauges. The results showed that strains at the bottom of the asphalt layer decreased as the vehicle speed increased. It was found that increasing speed from 32 to 56 km/hr resulted in a reduction of the tensile strains at the bottom of asphalt layer by 50 per cent. It was concluded that significant a speed effect is evident between speeds of 32 and 56 km/hr. It was recommended that rational pavement analysis models that consider the dynamic nature of traffic loads and viscoelastic properties of the asphalt material be investigated further.

Steyn and Visser [13] investigated the speed spectrum of 40 to 100 km/hr and showed that incorporating the effect of speed of moving load on pavement response significantly affected the pavement life. Attempt was made to create guidelines for incorporating this effect into South African pavement design procedure [12]. Theyse et al. [18] highlight aspects of South African Mechanistic-Empirical design method that required revision in order to allow for incorporation of most recently developed models and research findings. In this synthesis, it is recommended that the revised design method incorporate traffic loading wander and vehicle speed as part of traffic loading data input through frequency distribution histograms.

Building on previous research, ARA [14] incorporated vehicle operational speed into the pavement design procedure by including vehicle speed in selection of stiffness moduli of asphalt layers. This resulted in preparation of guidelines that were included in the MEPDG manual.

### *1.3. Influence of traffic speed on pavement performance*

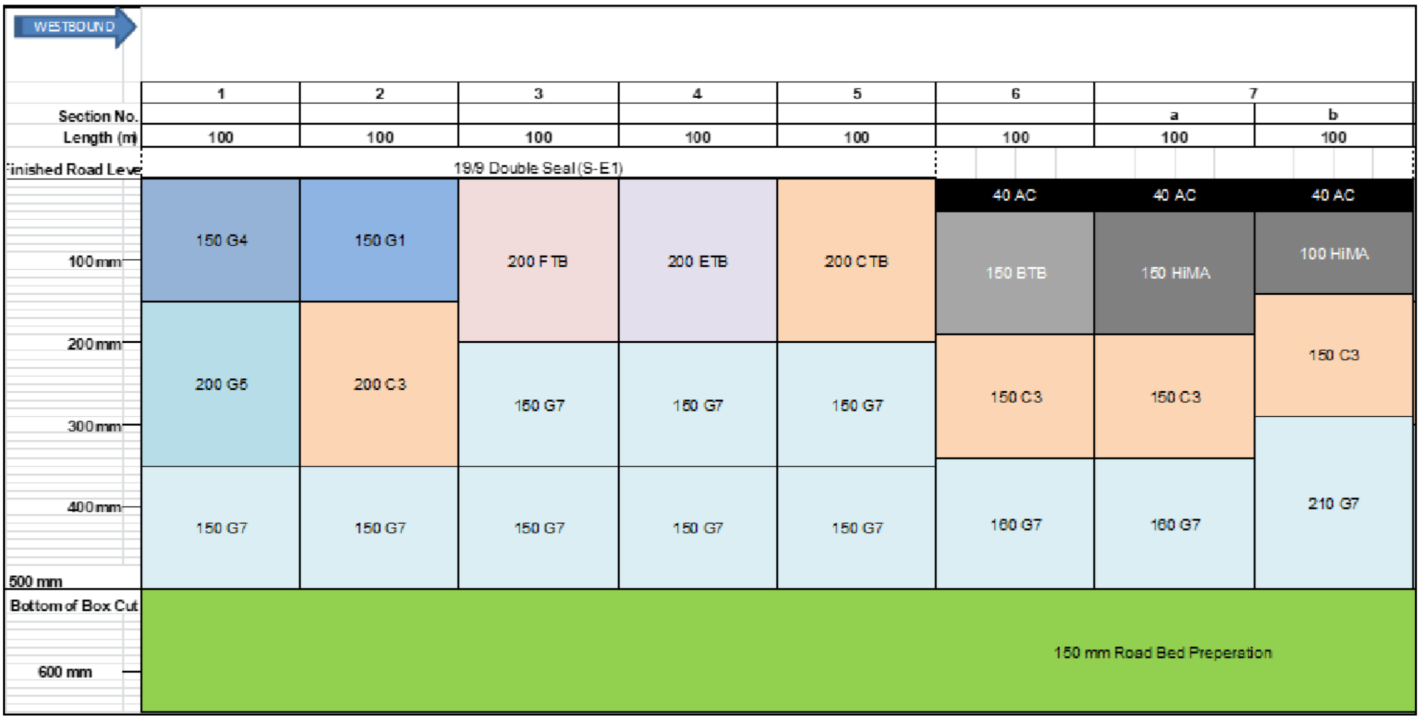
Most pavement systems in South Africa are constructed with thin surfacing (<50mm thick) [8]. The influence of truck speed on pavement response is revealed in the analysis of truck-pavement interactions under static or dynamic loading conditions. The previous section has shown that truck speed has significant effect on the critical values of stress and strain at any location within the pavement system as computed using the multi-layered linear-elastic system. In turn, these critical values from response model are used to determine the performance of the pavement system through transfer functions, also referred to as damage models.

Hugo et.al [19] evaluated performance of asphalt paving mixes using the Model Mobile Load Simulator (MMLS3) under different load frequencies as a test variable to simulate harsh trafficking conditions. A synthesis of national and international case studies was conducted. It was concluded that a decrease in MMLS trafficking speed resulted in an increase in the rate of rutting, especially at temperature of 60ºC. Bodin et al. [20] and Ahmed [21] investigated the temperature-dependent viscoelastic behaviour of asphalt pavements as response to load under varying temperature and traffic speed. The main objective was to develop a method to determine an Equivalent Asphalt Modulus (EAM) for the asphalt layer, which represents the effect of temperature and loading speed on the critical tensile strains. Results showed expected trends of the equivalent asphalt modulus increasing with increasing traffic speed and decreasing with increasing temperature.

## 2. Experimental program

The instrumented experimental section is located along road R104 between Rayton and Bronkhorstspruit, in Pretoria east. The experimental test section was constructed with ten sections with different pavement structures, ranging from flexible, rigid and segmental pavement structures. However, this paper only focuses on the eight flexible pavement sections constructed of natural and engineered pavement materials ranging from granular, cemented to bituminous layers. Fig. 1 summarises pavement structures on these eight sections.

The pavement material class acronyms in Fig. 1 are explained in Table 1.




*abbreviations explained in Table 2

Fig. 1. Flexible pavement systems on SANRAL R104 experimental section.

Table 1
Summarised description of pavement material classes used on R104 section.

| Class | Description | Class | Description |
|---|---|---|---|
| FTB | Foam treated base | G1* | Crushed stone layer |
| ETB | Emulsion treated base | G4* | Gravel layer- CBR>80% |
| CTB | Cement treated base | G5* | Gravel layer- CBR>45% |
| HiMA* | High modulus asphalt | G7* | Gravel layer -CBR >20 |
| EME | Enrobés à Module Elevé | C3* | Cement treated gravel layer-UCS 1.5-3 MPa |
| AC | Continuously-graded Asphalt | | |

* EME was referred to as HiMA in South Africa during the early days of transferring of the EME technology

### *2.1. Pavement instrumentation*

Pavement response is generally measured in terms of deflection, strain or stress. Measurement of temperature and moisture of the pavement system is also critical to pavement performance monitoring. The eight sections were therefore instrumented with some of the following sensors:

1. eMU coils (inductive coils) - measuring vertical and horizontal strain (elastic and permanent);
2. Strain gauges - measuring vertical, longitudinal and transverse horizontal strains;
3. Pressure cells – measuring stresses;
4. Multi- Depth Deflectometers (MDD) - measuring vertical deflections in relation to the anchor located at the bottom of the test hole, and
5. Thermocouple and Time-Domain Reflectometers (TDR) - measuring pavement temperature and moisture.

Fig. 2 shows a schematic presentation of the instrumentation in the pavement systems. This study focused on deflection measurement using MDD data.

Traffic loading on the pavement system was applied by controlled runs of the SANRAL owned Traffic Speed Deflectometer (TSD) truck. The TSD in Fig. 3 consists of a prime mover and a 8.2 t single axle semi-trailer fitted with dual wheels. The 8.2 t axle load which translate to 80 kN per axle corresponds to the South African standard design load. A tire inflation pressure of 700 kPa was maintained on all the wheels at all times. Traffic loading and testing was conducted under ambient temperature and no environmental conditions were controlled. Most test runs were conducted during the day from 9:00 to 16:00.

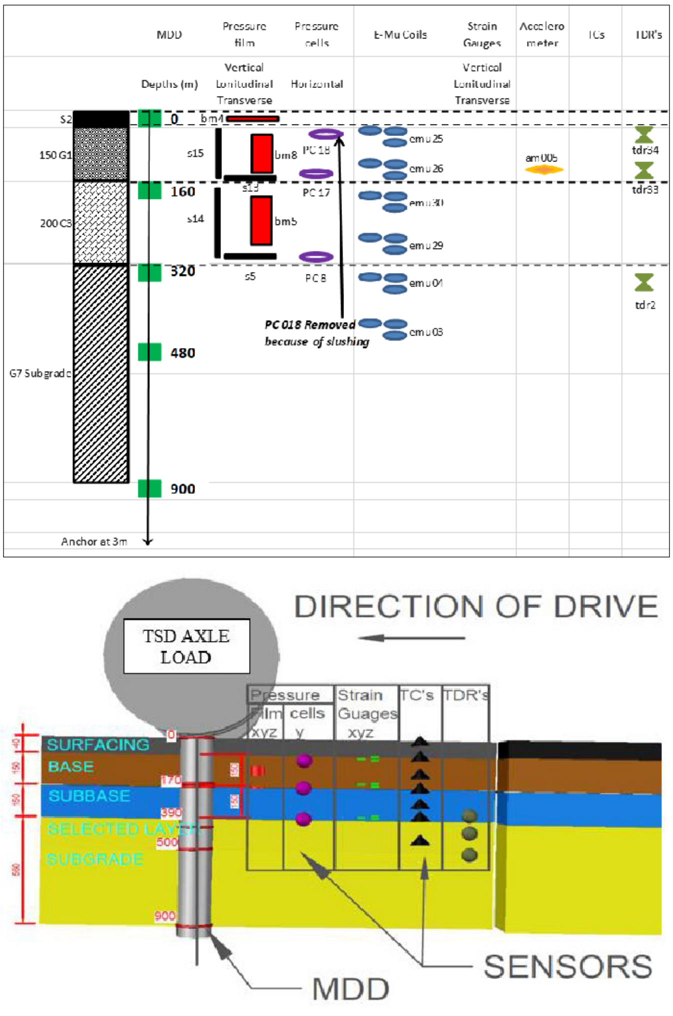



Fig. 2. Instrumentation of the pavement systems and traffic loading.

In this study the TSD was used to provide controlled traffic loading in terms of axle load, speed and wander. The TSD was ran at speeds of 2, 5, 10, 20, 30, 40, 60, 80 and100 km/h. Fig. 4 shows wander of 0, 192.5 and 500 mm offsets from the MDD used during test runs. The MDD was used as the reference and target point with centre of left rear double wheels running at either 0 mm offset, ±192.5 mm and ±500 mm. A dashboard laser guide was used to guide the driver towards the target wander lines. The TSD on-board data storage/retrieval system further provided speed and test run file logs.

## 3. Pavement response measurement

The MDD measures the transient pavement response induced by the moving axle load. Unlike equipment such as deflectographs that measure actual deflection bowl at each instant, the MDD measures a time series deflection with depth as the axle load approaches and passes through the sensor location (Fig. 5). The graph represents the time series transient response of the pavement at the sensor location as the truck approaches and drives past the test point from right to left.

### *3.1. Effect of vehicle speed on pavement response*

In order to investigate the effect of speed on the deflection, an excel based code was prepared to extract the rear axle maximum


Fig. 3. SANRAL Traffic speed deflectometer truck on test section.

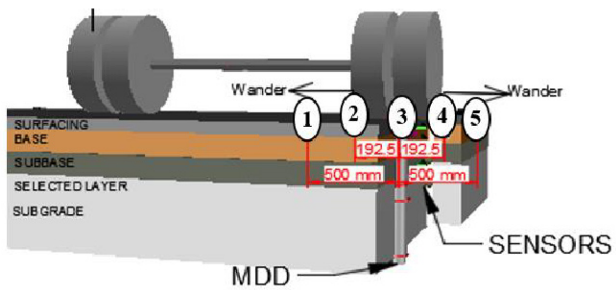



Fig. 4. Schematic views of the test section setup.

deflections from each test run. The processed data were grouped into data sets that averaged to an off-set of the centre of the rear dual wheel from the centre of the MDD. This was analysed and regression performed between speed and elastic surface deflections.

Fig. 6 presents relationship between speed and elastic surface deflection. The flexible pavement systems are further categorised into three categories; namely low, medium and high stiffness pavement systems.

The pavement structures investigated vary from low stiffness granular base and subbase to high stiffness cemented and bitumen treated base and subbase (Fig. 6) . The high stiffness EME base placed on cemented subbase pavement structures has the least deflections but it is significantly sensitive to change in truck speed. The figure further indicates that granular base with double seal surfacing display the highest elastic surface deflections, but it is less sensitive to changes in truck speed.

### *3.2. Operating speeds of Deflection and performance measuring equipment*

Deflections measurements are the most direct and popular method used to derive the E-modulus of pavement layers mostly because the theoretically calculated pavement response in terms of deflections can be directly compared with the measured response in terms deflections. Consequently, the use of deflection measurements is identified as an important input for the accurate characterisation of the pavement materials. Various deflection measuring equipment are available on the market which use different techniques to measure field deflections. These equipment include the Benkelman Beam, Falling Weight Deflectometer (FWD), Road surface Deflectograph (RSD) and Traffic Speed Deflectometer (TSD) [22,23]. Table 2 shows the speeds under which different deflection measuring equipment is considered to operate or simulate;

In order to predict future pavement behaviour transfer functions in terms of one or more failure theory are used to determine the life of layers in terms of a specific distress criterion. Heavy Vehicle Simulation is used in an Accelerated Pavement Testing (ATP) programme to determine performance of pavement systems. HVS testing is done under a slow moving (less than 15 km/h) wheel load which approximates static wheel load [2]. Alternatively an ATP MLS machines have been developed in South Africa to simulation full scale traffic loading and test the performance of pavement structures for development of pavement performance models. MLS 3 can run at speeds up to 9 km/hr where as the full scale MLS10 machine can operate at up to 26 km/h.

### *3.3. Simulation of moving load*

Experimental measurements have shown that the magnitude of elastic surface deflection of a pavement system depends to some extent on the speed of the moving load. The effect of the speed on pavement response to traffic loading varies with pavement system type. Using the formula $f' = 1/2\pi t$ and $v=2\pi fR$ , speed of moving load is converted to loading time and cyclic frequency (Hz) - where, $v$= speed (m/s), $t$.= loading time (s), $f$.=frequency (angular) (rad/s) and $R$= radii of the tyre (m). It important however to note inaccuracy concerns raised by Al-Qadi [7] related to these formula to simulate and relate vehicular speed to frequency used in loading specimen in the laboratory.

Fig. 7 shows relationship between speed and frequency as created from typical data provided by MPDEG for thin surfaced pavement systems. This figure is further used to show the typical ranges of speeds in which different deflection measuring equipment operate in. The same is used to determine corresponding frequency applicable to the determination of complex modulus from the laboratory determine master curve for asphalt materials.

Fig. 8 shows how use of specific deflection measuring equipment would relatively influence the determination and selection of complex modulus of an asphalt layer. It also shows the need for appropriate processing of TSD deflection data to take into account the influence of operating speed. Depending on the operating speed on a given pavement system, complex modulus could range from value (a) for speeds below 10km/h to value (d) for speeds above 90 km/h.

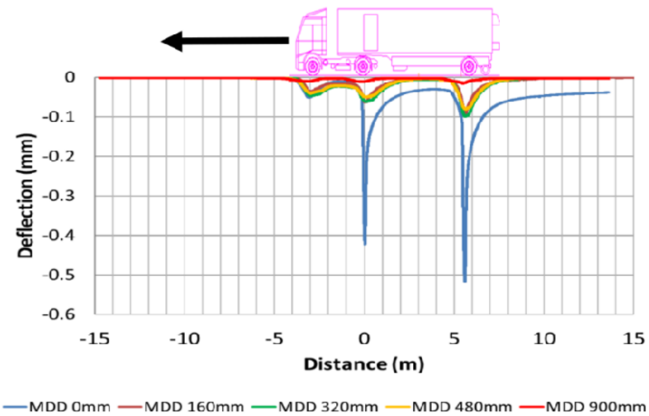



Fig. 4. MDD deflection measurements of TSD single pass at zero offset from sensor.

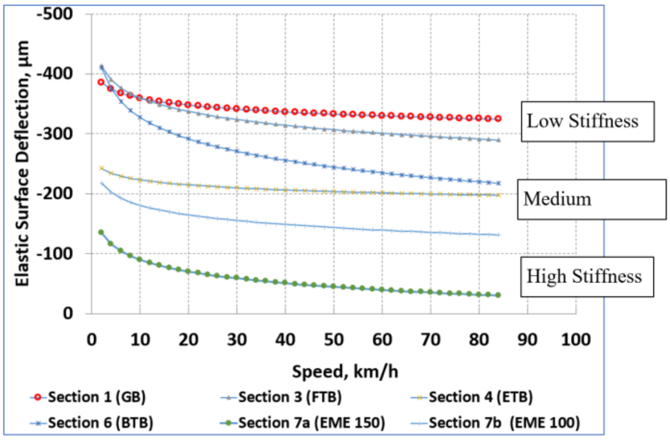



Fig. 6. Effect of speed on deflection of different pavement structures trafficked at 150-200 mm offsets.

Table 2
Operating speeds for deflection measuring equipment.

| Deflection measuring equipment | Speed (km/h) |
|---|---|
| Benkelman beam and road surface Deflectograph | 10-20 |
| Falling weight deflectometer | 50-60 |
| Traffic speed deflectometer | 5-100 |

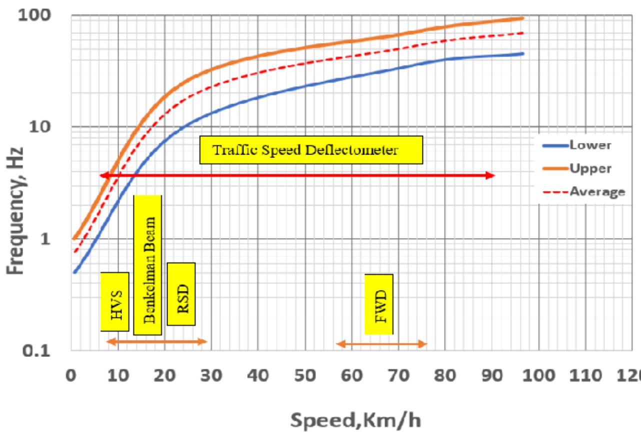



Fig. 5. Relationship between loading speed and frequency.

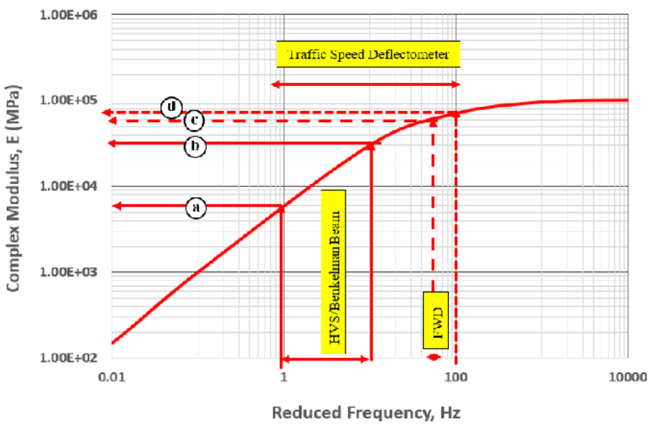



Fig. 6. Influence of type of deflection measuring equipment on determination of complex modulus from a typical master curve.

### 3.4. *Characterization of the pavement systems using Pavement structural number*

Pavement Number (PN) Method [24] was developed in South Africa for flexible pavement systems from a pavement performance data. The PN-based design method is a simple, robust and reliable approach to determining the structural capacity of a flexible pavement structure. The method is based on Structural Number (SN) concept and ranks pavement system in terms of PN that range from 0 to 70 which relates to the structural capacity of the pavement system. Considering that the PN takes into account the materials properties of the entire pavement structure, it makes a good complement to the maximum deflection values used in developing the speed effect models.

The six experimental pavement systems are evaluated using the PN method and assigned PN values. Table 3 shows that granular base pavement systems have lower PN values than the EME base pavement systems. This correlates well with deflections shown in Fig. 6 and hence gives an opportunity to link deflection, PN and operating speeds as shown in Fig. 9.

### 3.5. *Application of relationship between Speed Adjustment Factors and Pavement Number*

Normalising the elastic surface deflection values from Fig. 6 yields dimensionless values presented in Fig. 9. The normalized values are referred to in this paper as Speed Adjustment Factors (SAF). These factors can be used to adjust deflection measurements taken at given speed to elastic deflections expected at a different speed.

$$\delta_a = \delta_m * f(T(x,t), S(t), B(x)) = \delta_m * SAFa/SAFm \quad (2)$$

where, $\delta_a$ = Deflection adjusted to target speed *Sa*, $\delta_m$ = Deflection measured at speed *Sm*, *T(x,t)*, =temperature change above a reference state as a function of location and time, *S(x,t)*, = operating speed, as a function of location and time, *B(x,t)*, = Base type (PN value), as a function of location and time, $SAFa$ = Speed Adjustment Factor at target speed *Sa*, and $SAFa$ = Speed Adjustment Factor at measuring speed *Sm.*

### 3.6. *Proposed application of SAFs in pavement evaluation*

The APT machines operate at speeds of less than 26 km/h (HVS and MLS operate at maximum speeds of 12 km/hr and 26 km/hr respectively) and hence evaluating the pavement systems using deflection data taken at speeds above 30 km/h is of concern. It follows therefore that the Mechanistic -Empirical models that employ models from these ATP equipment should take these speed ranges into consideration. The SAFs offer an opportunity to incorporate effect of operating speeds in the flexible pavement assessment and evaluation procedure.

Firstly, it is proposed that the highway operating speeds during critical peak hours should be determined and the deflection measurements from a given equipment be adjusted to reflect the response under the targeted highway operating speeds. Secondly, the SAFs be used to adjust the deflection data to speeds that correspond to the speeds used during APT machines. This ensures that the deflections reflect the response that is expected during the APT program and more importantly harmonises speed conditions for the response model and damage models.

In the case of TSD, the SAFs provides a method for normalising the measured elastic surface deflections bearing in mind that the operating speeds of the TSD are controlled by the road traffic conditions. For instance, on a given pavement structure with PN =29, deflections measured at speed of 70 km/h is adjusted to speed of 30 km/h by SAF of 0.6 and deflections taken at speed of 10 km/h are adjusted to target speed of 30km/h by using SAF of 1.6 (Fig. 10).

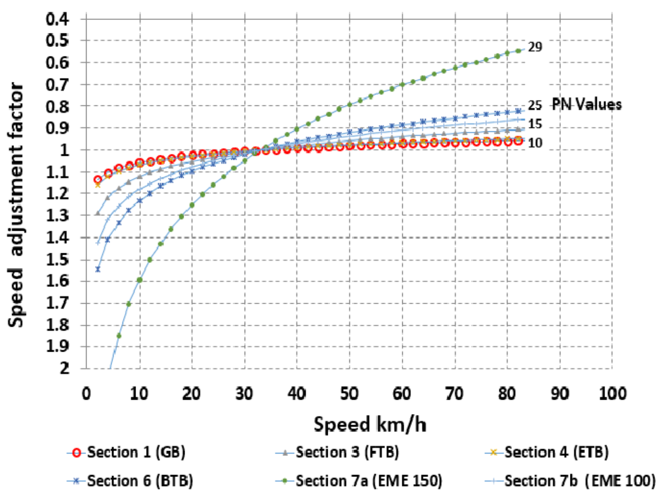



Fig. 7. Speed adjustment factors for 200 mm offset test runs.

Table 3
Pavement structure numbers for the experimental sections.

<table>
<tr><th>Pavement structure</th><th>Pavement number</th><th>Pavement structure</th><th>Pavement number</th></tr>
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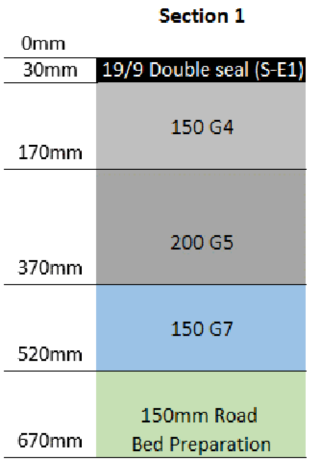
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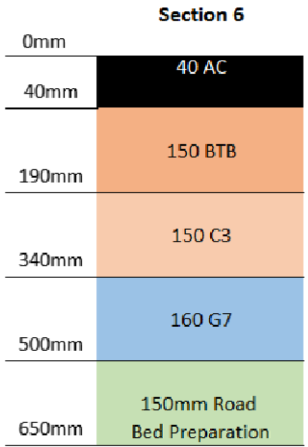
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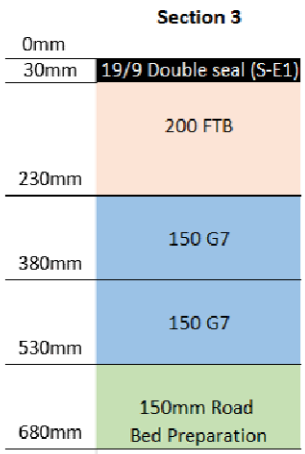
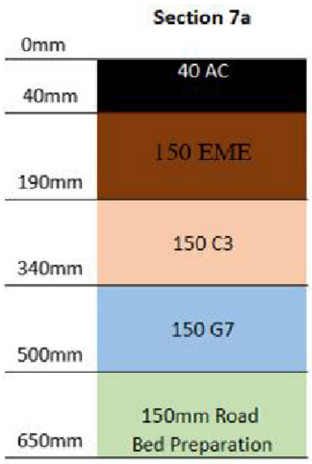

</td><td>15</td><td>Section 7a: EME base(150mm) on cemented subbase

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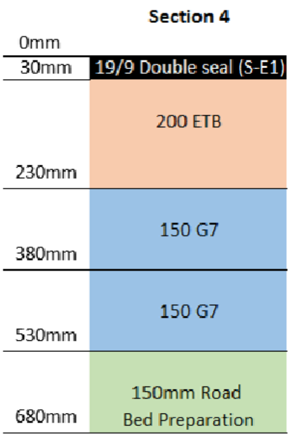
<tr><td>Section 4: Emulsion treated base on natural gravel subbase

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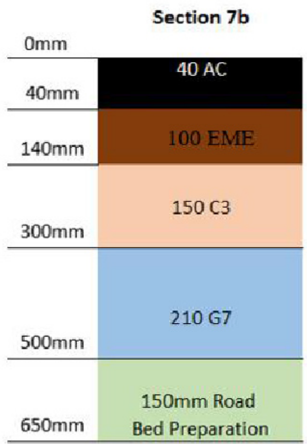
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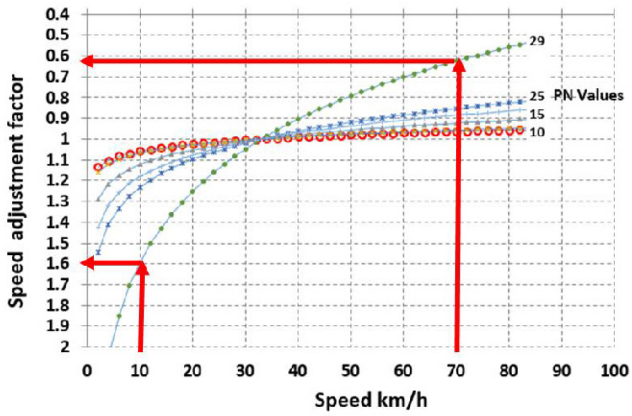


Fig. 8. Typical example of adjusting TSD deflections taken at different speeds.

## 4. Conclusions

The present study investigated and proposed a methodology for adjusting deflections measured at different moving load speeds using Speed Adjustment Factors (SAFs). From the results (although limited to the pavement systems investigated) the following are concluded:

1. The speed of moving load has significant and varying influences on the dynamic response of different flexible pavement systems;
2. The proposed methodology for adjusting the deflections using SAFs allows the pavement engineer to take into account the influence of speed on surface deflection values and appropriately process the data as input into pavement response modelling.
3. SAFs adjusted deflections, as input into response model, would yield critical output parameters that mimic the conditions during APT
4. Measurement and interpretation of elastic surface deflections data from existing road should take into account the speed/frequency of the deflectometers, and
5. Selection of type of flexible pavement systems including surfacing binder grade, thickness of layers and stabilisation agent, in particular on road rehabilitation projects, should take into account the average truck speeds (congestion levels and road grades).

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