Evaluation of rutting of asphalt concrete pavement under field-like conditions

Safwat Fadhil Said[1, a], Abubeker Worake Ahmed[1, b], Håkan Carlsson[1, c]

[1] *Pavement Engineering, VTI, Linköping, Sweden*

[a] safwat.said@vti.se
[b] abubeker.ahmed@vti.se
[c] hakan.carlsson@vti.se

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ABSTRACT

Permanent deformation, or flow rutting, in bituminous layers is a regular distress mode in flexible pavements that is manifested as an excessive deformation of bituminous material along the wheel paths. Rutting gradually increases with repeated loading from heavy traffic. The asphalt concrete layer's low shear resistance and inadequate compaction during construction may have a significant impact on rut formation. A reasonable interpretation of vehicle loading is however crucial in prediction of rut formation in flexible pavement surfaces using mechanical pavement design approaches. The interpretation of traffic data regarding axle load, single or dual wheels, tyre-pavement contact stresses, vehicle speed and lateral wander have a significant effect on the accuracy of rut prediction. The objective of this study is to evaluate the resistance of asphalt mixes and the influence of traffic loading on rut prediction using a linear viscoelastic approach called PEDRO (PErmanent Deformation for ROads) for predicting both the compressibility and shear deformation of asphalt layers under field-like conditions. The results indicate that the adopted procedure is effective for a reasonable evaluation of bituminous mixtures and rut development, as well as to quantify the influence of vehicle variables on rut formation.

Keywords: Design of pavement, Mechanical Properties, Permanent Deformation, Viscosity

1. INTRODUCTION

Rutting is a major distress in asphalt pavements. Manifestation of rutting depends on many factors, such as traffic variables, pavement structure, material characteristics and climate conditions. Traffic loading consists primarily of vehicle axle load configurations, axle loads, tyre pressures, speeds and transversal distributions of vehicles. Vehicle loading induces stresses in the pavement through the tyre-pavement interface. The speed of vehicle loading influences the magnitude of stresses and strains in the pavement due to the viscoelastic characteristics of the bituminous mix and the mix properties in turn depend on the pavement temperature. The magnitude of stresses and strains varies with both depth and horizontal distance from the loading centre of the tyre-pavement contact area. These parameters have a substantial effect on the precision of rut depth prediction on the pavement surface. The impact of wheel load is usually approached by converting axle load into Equivalent Standard Axle Load (ESAL) using a load equivalence factor. This factor is empirically determined from field tests and depends on traffic, structure, materials and climate in relation to pavement distresses, usually surface cracking but may also be in respect of average deterioration of several distress mechanisms. However, different types of deterioration may results in different load equivalence factors. In some recent investigations, the axle load spectra (distribution of axle loads over a year) were estimated from a weight-in-motion system for consideration of the actual traffic in a road section. Ideally, one should combine the hourly traffic distribution with the hourly temperature distribution over a year due to the importance of temperature for rut prediction. However, the number of ESAL repetitions is usually used in practice due to simplicity of the ESAL in interpretation of traffic data. Further, the tyre-pavement interface is assumed to have a contact stress equal to tyre pressure. Investigations in recent decades [1, 2, 3 and 4] have reported that the tyre-pavement interface pressure may differ from the tyre inflation pressure and is non-uniformly distributed within a circular contact area, which may induce considerable differences in pavement damage from using different types of tyre and varying tyre load and pressure. The studies recommended detailed vehicle traffic data and a better description of tyre-pavement stresses to improve the predictive capability of the mechanistic pavement design models for use in practice. The University of Nevada's 3D-Move Analysis Software [5] for analysis of asphalt pavement stresses can take into account pavement responses under a broad range of tyres for practical use in pavement evaluation.

The scope of this paper is to highlight the influence of asphalt mixes and traffic loading in prediction of rut development in bituminous pavement layers under field-like load conditions with respect to axle load, axle load configuration, tyre-pavement contact stress and influence of lateral displacement of traffic at ambient temperature, using the linear viscoelastic predictive approach PEDRO [6, 7 and 8] for prediction of rut development in asphalt pavement layers.

2. PAVEMENT STRUCTURE AND MATERIAL CHARACTERISTICS

The semi-rigid pavement section on the E6 highway, located in the west of Sweden, was opened to traffic 1996. The pavement structure, shown in Figure 1, consists of a 60-mm densely graded asphalt concrete layer as a binder layer. The mix designation of the binder layer is ABb16 70/100. The maximum aggregate size is 16 mm with a binder content of 5.8% bitumen type pen 70/100 and an air void content of 4.5%. The cement-stabilized layer is 255 mm thick. No permanent deformation is expected in unbound layers and subgrade due to present of cement-stabilized layer. The structure is topped with a wearing course of stone mastic asphalt type SMA16 70/100 with a maximum aggregate size of 16 mm. The bitumen content is 6.2% of type pen 70/100 and the air void content 4.8%. The aggregate type in both mixes is quartzite with 100% crushed aggregate. The unbound base and sub-base materials are crushed aggregate. Further details of the test road's semi-rigid pavement structure has been reported in Wiman [9]. The complex viscosity of the asphalt concrete materials was estimated as a function of the complex shear modulus and loading frequency at the peak of the phase angle by testing asphalt concrete cores using frequency sweep shear tests [10]. The average complex viscosity of the asphalt concrete mixtures is shown in Figure 2 and are based on testing three specimens per mix. The complex viscosity of an alternative mix used for binder layers with polymer-modified bitumen of type ABb 22 50/70-53 with 6% EVA [11] is also presented in Figure 2. Increased viscosity from using polymer-modified bitumen based on pen 50/70 and using a maximum aggregate size of 22 mm is obvious in comparison with the conventional binder mix.

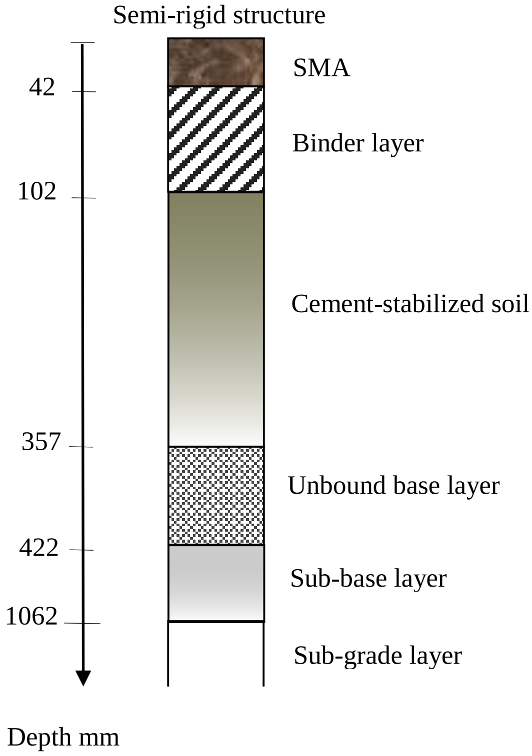

Figure 1: The pavement structure of a semi-rigid pavement

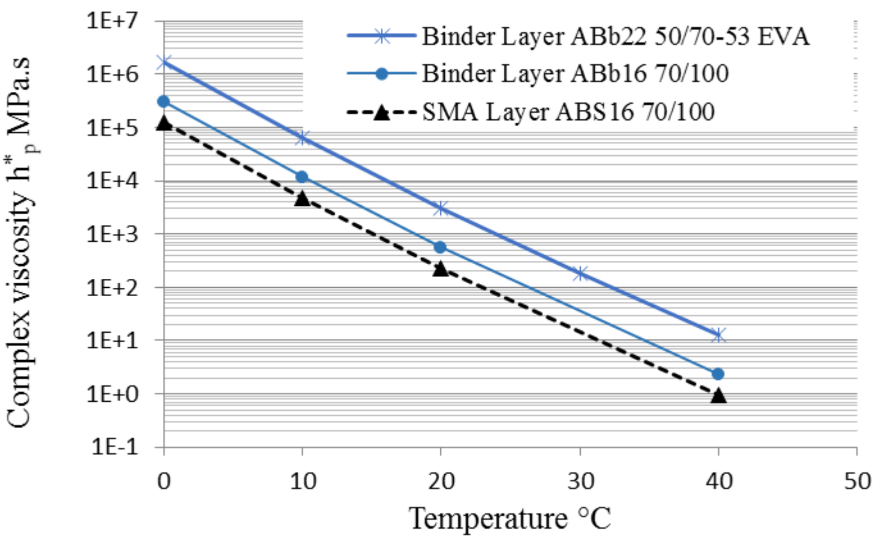

Figure 2: Complex viscosity of the asphalt concrete mixes in relation to temperature

2.1 Rut depth development

A low-speed laser profilometer called Primal was used to measure transverse profiles of the test section, illustrated in Figure 3. The profilometer produces measurements with an accuracy of 0.1 mm. Two measurements a year were performed, in April and October. Rutting during this period refers to deformation in the asphalt pavement due to heavy traffic. The increase in rut depth between October and April, i.e. the winter period when temperatures are lower than 5 °C, refers to wearing due to studded tyres. Furthermore, no permanent deformation was expected in other layers of the structure due to the cement-stabilized base layer under the bituminous layers. Figure 3 shows the rut depth development due to permanent deformation in bituminous layers in the test road (taken from Wiman et al [9]). The number of Equivalent Standard Axle Loads (ESALs) (100 kN) was estimated using the fourth power law.

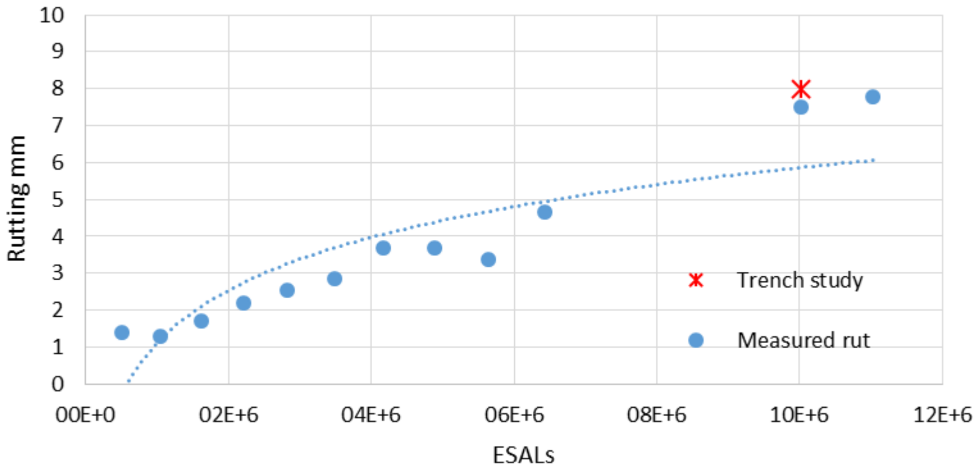

Figure 3: Rut depth development due to permanent deformation in asphalt layers as a function of ESALs

2.2 Trench study

In 2010, the test section was trenched to identify the cause of surface rutting. The trench profile and the pavement beam extracted for laboratory study are shown in Figure 4. The maximum rut depth in the left wheel path was 14 mm. Wear due to studded tyres was 6 mm according to Wiman et al [9] and no deformation was recognized in the cement-stabilized base layer. Consequently, 8 mm permanent deformation in the surfacing and binder layers after 14 years traffic (2.4 x 10^7 ESAL passages) was estimated from the trench study. Note that the rut depth given was based on the initial surface profile of the pavement section without including upward heaving outside the wheel paths. It was also doubtful whether the amount of deformation originating from the surface and binder layers could be measured accurately. The trench study resulted in approximately 0.5 mm deeper ruts than measured using the Primal profilometer; see Figure 3.

3. DESCRIPTION OF THE INVESTIGATION

It is well-known that the predicted rutting values from various prediction models may vary in comparison with existing pavement due to testing condition, axle load configuration, hourly variation of temperature, traffic speed, traffic lateral wander, etc. The objective of this investigation is to evaluate flexible pavement materials, highlight the importance of some of the traffic variables in evaluation of pavement rutting, and implement the PEDRO (PErmanent Deformation for ROads) model for rut prediction. More accurate estimation of permanent deformation in asphalt layers and accurate calibration of the model, detailed data of heavy vehicle parameters such as axle load distributions, axle load configurations and the types of tyres used together with their interface contact pressure, lateral wander of vehicles and hourly traffic and temperature distributions on the road section is required. In this particular study, permanent deformations in asphalt layers were predicted using the assumption in Table 1 with three types of tyres currently used as commercial tyres, viz. Goodyear 159A, 11R22.5 as dual tyre and Goodyear 425/65R22.5 and 495/45R22.5 as wide-base tyres. The tyre-pavement interface contact pressure with respect to tyre load and pressure in Table 1 was calculated according to references [4 and 5]. In addition to the conventional binder mix (ABb 16 70/100), estimation was performed with an enhanced binder mix, a polymer-modified binder mix with a maximum aggregate size of 22 mm (ABb22 50/70-53 EVA). Monthly average temperatures, see Figure 5, were used instead of hourly temperature distribution since axle load and hourly vehicle distributions were not available and also to limit the number of calculations. Temperature measurements for the period2003 – 2004 from a weather station (VViS 1336) located close to the test road section were therefore analysed. Air and pavement surface temperature data, at a sampling frequency of one measurement per hour, were used in this work. Hermansson's model [12] has been used to calculate temperature at the mid-depth of the surfacing and binder layers. Figure 5 illustrates the average monthly temperature at the road site based on 2003-2004 temperature measurements.

Figure 4: Pavement profile and extracted asphalt concrete beam

Table 1: Input data for prediction of permanent deformation in asphalt layers

Tyre type	Axle load kN	Tyre pressure kPa	Contact pressure kPa	Contact area cm^2
11R22.5, Dual	100	760	575	2 x 435 = 870
	124	482	522	2 x 594= 1188
	124	760	607	2 x 511=1022
425/65R22.5, Single	100	760	687	728
	124	482	420	1477
	124	760	735	843
495/45R22.5, Single	124	482	359	1727
Load applications	Equivalent Standard Axle Load (ESAL) using the 4th power law			
Axle load, kN	100 alternative 124			
Vehicle speed, km/h	90			
Standard deviation of lateral wander, m	0.29, 0.24 or 0.20			
Binder course	ABb 16 70/100 alternative ABb 22 50/70-53 EVA			
Temperature, °C	Monthly mean temperatures (see Figure 5)			

4. ESTIMATION OF PERMANENT DEFORMATION IN ASPHALT LAYERS

In this investigation, rut development in the road section (Figure 3) subjected to traffic loading over a 10-year period was predicted using a beta version of the linear viscoelastic model PEDRO, that is based on the calculated permanent vertical strain under moving load [6, 7 and 8]. The inputs to the PEDRO model include tyre-pavement contact pressure, vehicle speed and lateral wander, asphalt concrete layers' viscosities and thicknesses, and hourly traffic and

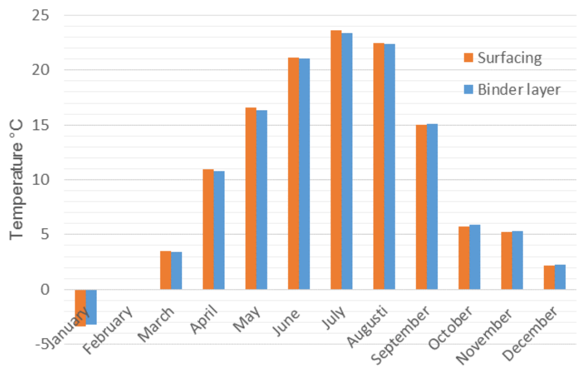

Figure 5: Monthly temperature distribution at the test road site

temperature distributions for asphalt concrete layers (hourly distributions were not used in this investigation). The model consists of two parts: one for calculation of compressibility representing the initial zone where a substantial decrease in volume is expected, and one for calculation of the flow rutting part of the deformation where almost no change in volume is expected. The deformation is calculated successively for each loading. The rut depth is calculated by integrating the permanent deformation over the thickness of the asphalt concrete layers with respect to number of load repetitions. The distribution of the vertical permanent strain under dual wheel load is illustrated in Figure 6 [13]. An example of data input interfaces is shown in Figure 7. The beta version of the PEDRO software may be downloaded from www.vti.se (from 2016).

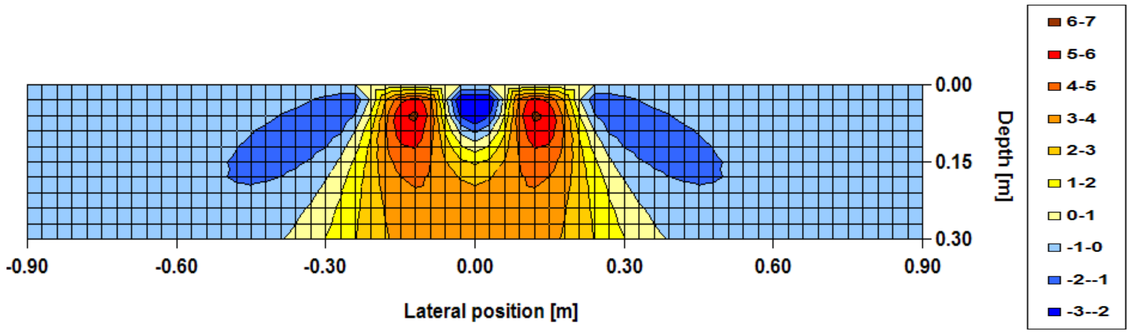

Figure 6: Distribution of the vertical permanent strain under dual wheel load using PEDRO [13]

Figure 8 shows average measurements of accumulated permanent deformation in the wheel path (from Figure 3) and estimated rut development as a function of ESALs on the test road. The inputs to PEDRO for the test road include 50/50 percent of dual tyre (11R22.5) and single tyre (425R22.5) axle load configurations with a lateral wander standard deviation of 0.29 m, vehicle speed, viscosity of asphalt concrete mixes, layer thicknesses and monthly average temperature (hourly traffic and temperature can be used if data is available), as described in Table 1. Note that the tested asphalt concrete cores were already aged at the time of testing (about 12 years old). The viscosity of the asphalt concrete for the 1st year prediction was decreased by 17% for ageing impact [14] that is necessary for estimation of the initial deformation. With regard to the above assumptions, a reasonable agreement between the estimated and the measured deformations is shown for the tested structure. The estimated rutting was calibrated with the field measurements using a single calibration factor (0.22) for the test section. It was not the objective of this study to develop a final calibration factor for the model since this requires complete data on climate and heavy vehicle parameters such as axle load configurations and hourly distributions, hourly distribution of temperature, tyre-pavement interface characteristics of the most frequent trucks on the road section, etc. The final calibration factor should be calculated after testing several road sections to determine a general calibration factor dependent on field variables.

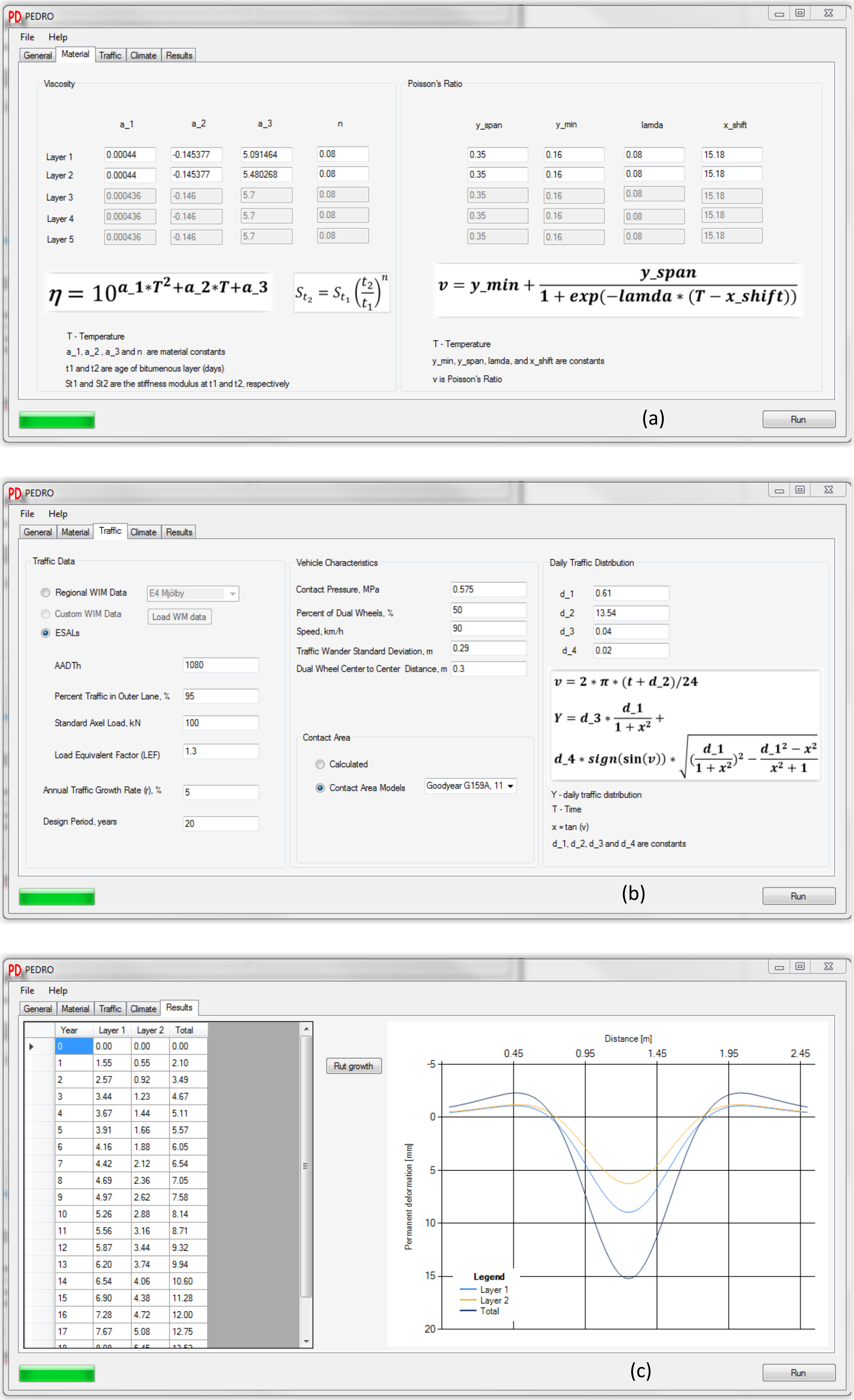

Figure 7: Input data interfaces in PEDRO, (a) material constants for viscosity and Poisson's ratio, (b) traffic data, and (c) typical results

4.1 Influence of asphalt concrete characteristics

Asphalt mixtures' content and properties are crucial parameters that determine the performance of a bituminous layer. The effect of mix properties on rut formation was investigated. The binder course of the pavement structure described above was replaced with an enhanced rutting-resistant binder mix. The complex viscosity of the binder layers with polymer-modified bitumen (ABb 22 50/70-53 EVA), Figure 2, is shown to have significantly higher viscosity than conventional binder mix used in the test section (Figure 1). Figure 9 shows the impact of the enhanced mix on the resistance to permanent deformation. It takes more than ten million ESAL applications to reach the same rut depth (4 mm) using enhanced binder mix, compared to about five million ESAL applications for the structure with conventional binder mix. Further studies of the effect of mix components would therefore be valuable in order to optimize mix design in respect of field conditions.

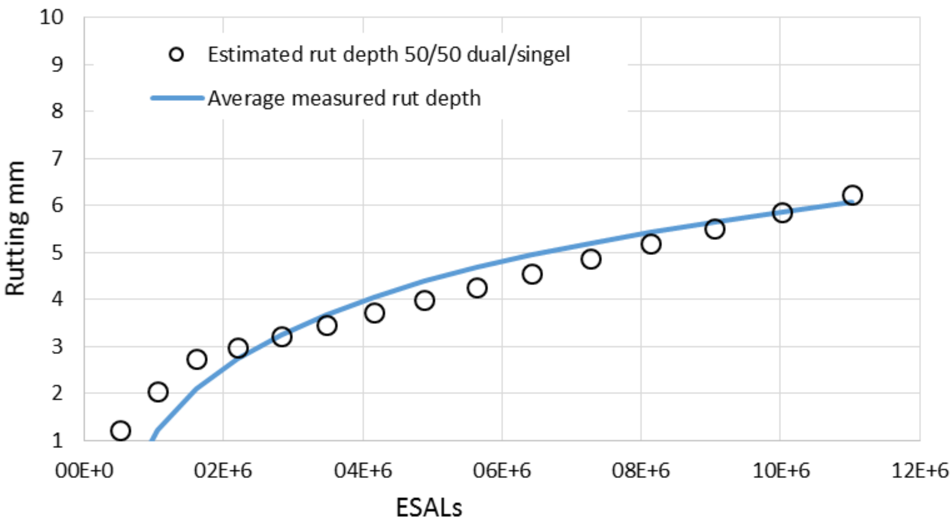

Figure 8: Average measured rut depth with rut development estimated using 100 kN, 760 kPa, 90 km/h and a standard deviation in lateral wander of 0.29 m

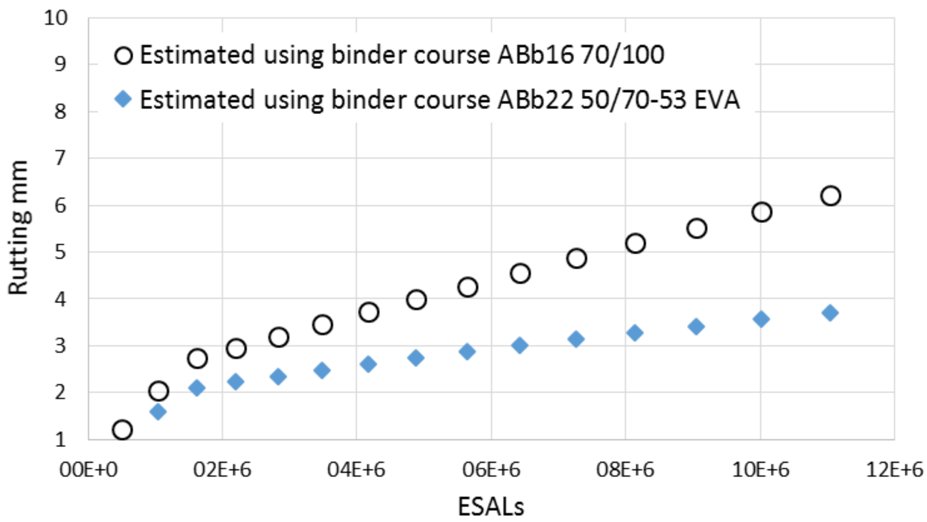

Figure 9: increased rutting resistance using enhanced mix with cumulative ESALs

4.2 Influence of vehicle variables

Influence of axle load

The impact of axle load configuration on rut formation may be modelled in PEDRO as a dual or single tyre through tyre-pavement interface pressure. A uniform contact stress within an assumed circular area in this work. However, non-uniform contact pressure may also be simulated in PEDRO by defining different stress at the centre and edge of the interface [15]. For a certain tyre load and inflation pressure, the contact area is determined according to Blab [4] or using the 3D-Move analysis software [5]. The impact of axle load on rut formation for the pavement structure described above is illustrated in Figure 10. Increasing axle load from 100 kN to 124 kN results in 29% more rutting in this case, or at 6 mm rutting the pavement withstands approximately one million more passages when loading with 100 kN. Note that investigation with different structures, bituminous materials and loading conditions may result in other differences. Optimization through modelling may thus be valuable for each road section.

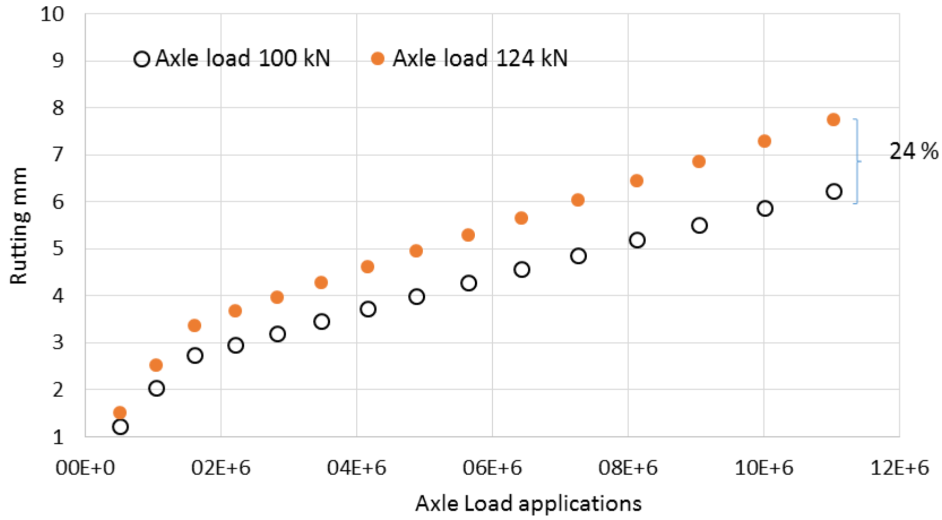

Figure 10: Impact of axle load on rut depth development using 50/50 dual (11R22.5) / single (425/65R22.5), 760 kPa, 90 km/h and lateral wander standard deviation of 0.29 m.

Influence of lateral wander

After initial rutting, mostly two years after construction, the flow rutting is primarily related to the lateral movement of the asphalt material that is induced by repeated shear stresses from heavy vehicle loading. This generates a depression under the wheel load and upheaval along the wheel path. In reality, vehicles along a road use somewhat different wheel paths, which results in a lateral distribution of traffic. This distribution is useful to slow the progression of rutting [16]. Using different axle load configurations and tyre widths therefore has an impact on rut development. Figure 11 shows that increasing the lateral wander of vehicles from a standard deviation of 0.24 m to 0.29 m causes the pavement to withstand almost two million more passages of ESAL applications at 6 mm rutting. The impact of lateral wander of heavy vehicles therefore cannot be ignored when predicting rut development in pavement surfaces. Lateral wander is mostly related to the width of the traffic lane and traffic planning, as in 2+1 road designs that have narrow lanes and more channelized traffic. Carlsson [17] reported a significant increase in rutting on 2+1 road sections, which is mainly related to heavy vehicles.

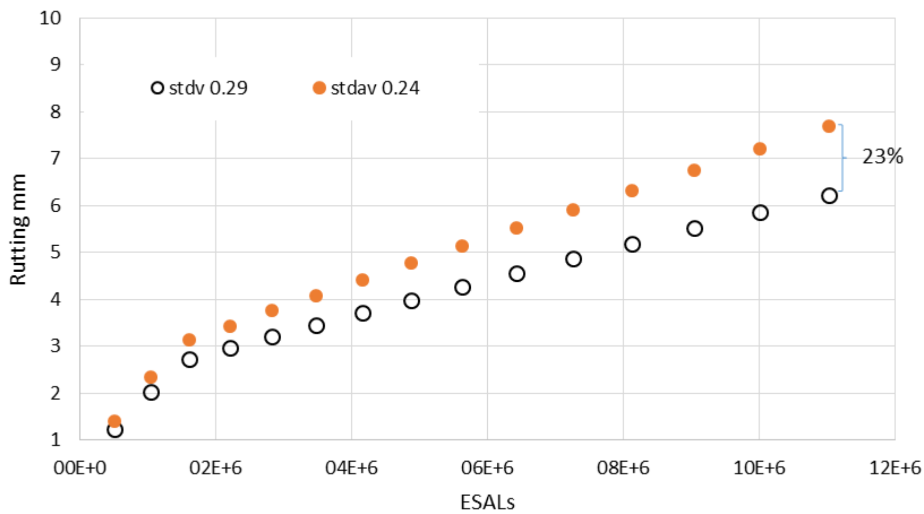

Figure 11: Influence of standard deviations of lateral displacement of vehicles on rut depth development using 50/50 dual (11R22.5) / single (425/65R22.5), 100 kN, 760 kPa at 90 km/h

Influence of axle load configuration and tyre type

It is known that considerable differences exist between different types of axle load configurations and tyres with respect to tyre-pavement interface stresses, which may induce considerable differences in pavement damage, including rutting, from using different types of configuration with varying tyre loads and pressures [1, 3 and 4]. Prediction of rutting might therefore be based on the dominant tyres in the region. Figure 12 illustrates the significant effect of using axle configurations with dual or single wheels and tyres with different contact width. Note that the difference between single and dual configurations increases with decreasing lateral displacement (decreasing standard deviation from 0.29 m to 0.20 m). Differences in rutting between the two single tyres, 425 and 495, are small in relation to lateral displacements but increase with decreased standard deviation since the difference in contact area is also small (Table 1).

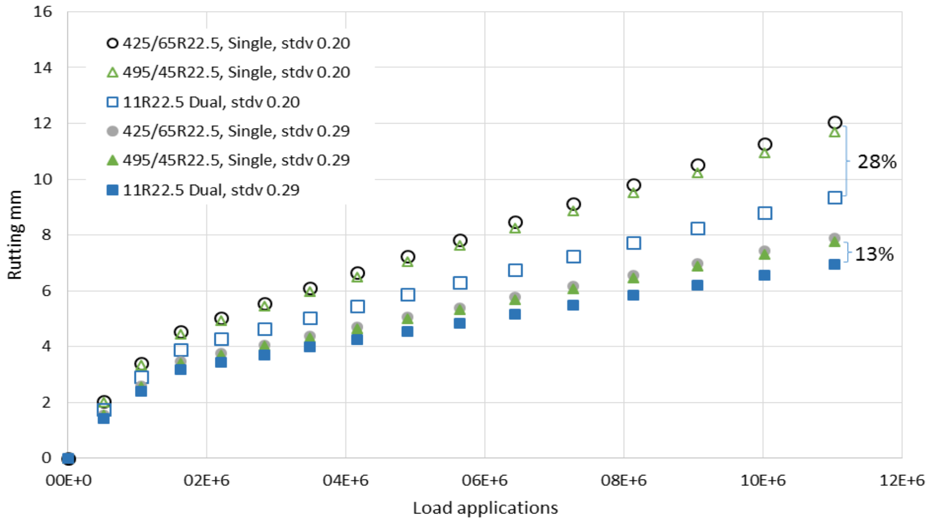

Figure 12: Influence of axle load configuration and tyre type on rut depth development at an axle load of 124 kN, 482 kPa and 90 km/h.

5. CONCLUSIONS

In this study, the PEDRO approach for rut prediction in asphalt concrete layers was used under field-like conditions. The sensitivity of the PEDRO model to mix properties and vehicle data such as axle load, dual and single axle load configurations, type and dimension of commercial tyres and lateral wander of traffic has been demonstrated. A proper understanding and evaluation of heavy truck loading is required to predict rut development in asphalt layers. Axle load configuration, tyre type and tyre-pavement contact stresses have a significant effect on rut formation. Lateral wander results in significantly lower rut depth with increasing lateral displacement of traffic, indicating that lateral wander has to be taken into account in road design and forecasts of rut development. This study shows that further investigations are needed to enhance the predictive capability of the design models, primarily vehicle data such as properties of tyres on trucks and distributions of different axle configurations for various regions/roads. Improvement of a general calibration factor for the PEDRO model that takes into account the effect of traffic variables, such as axle load, inflation pressure, vehicle speed, and climate conditions, would be valuable for its practical use.

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