INFLUENCE OF TRAFFIC VARIABLES ON RUT FORMATION IN ASPHALT CONCRETE LAYERS

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Abstract

Rutting in asphalt concrete layers is a frequent distress mode in flexible pavements. Surface rutting in a flexible pavement structure usually originates from all pavement layers and the subgrade. Flow rutting is defined as an excessive deformation of bituminous layers in the wheel paths which gradually increases with increasing numbers of vehicle load repetitions. In addition to traffic history and climate factors, flow rutting is affected by the properties of asphalt mixtures, especially at high temperatures and under loading of relatively long duration, when the mix properties are dominated by the viscous character of the material. A linear viscoelastic approach (PEDRO) for behaviour of asphalt concrete when subjected to a moving load has been adopted in this work. The PEDRO approach has the capability to estimate rutting in asphalt concrete layer under various axle load configurations and moving load conditions. Lateral wander of the traffic, which affects the transversal rutting profile, including the formation of upheavals, has been estimated. The influence of axle load, wide single-wheel axles, tire pressure, traffic speed and lateral wander of the traffic is discussed.

Keywords: Rutting, Asphalt Concrete Layer, Heavy Vehicles, Viscoelastic Model

1. Introduction

Despite the generally cold climate in Scandinavian countries, the temperature in flexible pavement can reach 50°C during the summer when the sun shines for more than 20 hours a day and flow rutting is therefore one of the most frequent types of distress on high volume roads. Surface rutting in a flexible pavement originates from all pavement layers and the subgrade. Flow rutting is defined as an excessive deformation of bituminous layers in the wheel paths which gradually increases with increasing numbers of vehicle load repetitions. Flow rutting in an asphalt concrete layer is caused by two mechanisms: densification, which is a decrease in volume and increase in density of an asphalt concrete layer under repeated traffic loading, and shear deformation with the formation of upheavals, i.e. displacements of material caused by traffic load induced shear stresses (Figure 1). In addition to traffic history and climate factors, flow rutting is affected by the properties of asphalt mixtures, especially at high temperatures and under loading of relatively long duration, when the mix properties are dominated by the viscous character of the material. Flexible pavements should therefore be designed, among other things, with respect to resistance to permanent deformation under various moving load conditions.

The permanent deformation developed under repeated wheel load can be divided into three zones: initial, secondary and tertiary, as illustrated in Figure 2. The mechanism of permanent deformation in asphalt concrete layers has been described by many researchers, for example (Eisenmann and Hilmer 1987, Sousa et al. 1991, Verstraeten 1995, Kaloush and Witczak 2002, Blab and Harvey 2002). The initial deformation zone is primarily caused by an increase in density, called post-compaction from repeated traffic loading, mostly during the first two years after opening the road. In the second zone the deformation develops with time at a constant rate although at a decaying rate. At this stage the deformation is primarily related to the lateral movement of material, which is induced by repeated shear stresses from heavy vehicle loading. This generates depression under the wheel load and upheaval along the wheel path. To calculate rutting under wheel load it is therefore crucial to include the influence of lateral wandering of the traffic.

Traffic loading is the most important design factor for pavements, although the pavement structure, materials and climate are also essential parameters in this respect. Not only the number of heavy vehicles, but also the axle load and configuration, tire type and pressure, traffic speed, as well as the lateral wander of the traffic, which is related to the width of the lane also have an impact (OECD 1991, Blab and Harvey 2002, Sebaaly 1998).

In this work, the algorithms of a linear viscoelastic model have been adapted to predict permanent vertical strain in a typical asphalt concrete pavement subjected to a moving load. The package used here to calculate the permanent deformation of asphalt concrete layers is called PEDRO (**PE**rmanent **D**eformation of asphalt concrete layer for **Ro**ads) (Said et al. 2011).
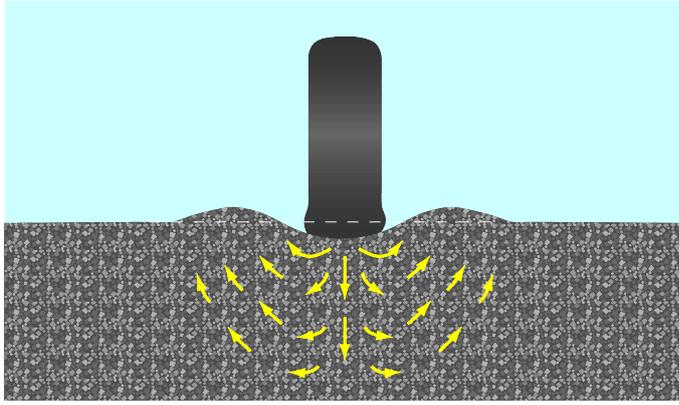
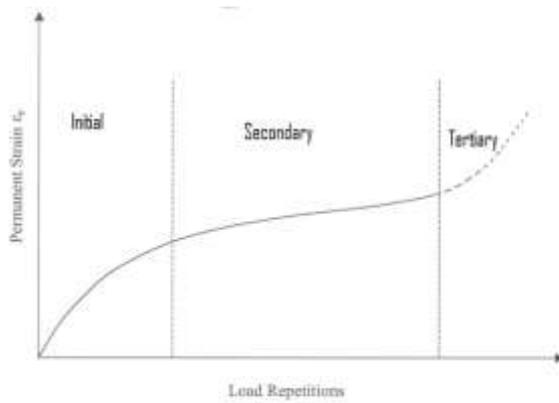**Figure 1 - Illustration of mechanism of flow rutting in asphalt concrete**

Figure 2 - Typical rut developments due to repeated loading

2. Objective

The purpose of this study was to evaluate the influence of traffic parameters on rut development in asphalt concrete layers. The predictive model, PEDRO, is based on the number of passages of wheel loads, traffic speed, axle load configuration (single or dual wheel load), tire pressure, influence of lateral wandering of the traffic, the pavement structure and the mixture properties at various temperatures. The aim is to present the influence of traffic variables on rut development in asphalt concrete pavement layer.

3. Predictive Model PEDRO

The PEDRO package (Said et al 2011) has been used in this work to study the effect of traffic variables on rut formation in asphalt concrete layers. The vertical permanent strains (ε_p) encountered in the initial and secondary zones were calculated at various depths and lateral positions in the asphalt layers under a moving load using Eqn. (1). The rut depth was

calculated by integrating the permanent deformation over the thickness of the asphalt concrete layer.

$$\varepsilon_p = \frac{\sigma_0 \cdot (1 - 2\nu)}{V \cdot \eta_A} \cdot \mathrm{Re}\left[\sqrt{(z+ix)^2 + a^2} - (z+ix)\right] + \frac{\sigma_0 \cdot z}{V \cdot \eta_A} \cdot \mathrm{Re}\left[1 - \frac{z+ix}{\sqrt{(z+ix)^2 + a^2}}\right] \quad \ldots 1$$

where

ε_p = the permanent vertical strain in µm/m

σ_0 = tyre pressure in Pa

a = radius of contact area in m

ν = Poisson's ratio

z = depth from road surface in m

V = vehicle speed in m/sec

η_A = viscosity of asphalt mix in Pa s

x = distance from loading centre in m

i = $\sqrt{-1}$

The viscosity of the asphalt concrete materials was estimated as a function of the shear modulus and the phase angle by testing asphalt concrete samples with frequency sweep tests. To estimate the viscosity of an asphalt mix, researchers have generally used the complex viscosity ($\eta^* = G^*/\omega$), the real part of the viscosity ($\eta' = G''/\omega$) or the zero shear rate viscosity (ZSV) to evaluate the rutting characteristics of asphalt concrete materials (Hopman and Nilsson 2000, Björklund 1984, Collop et al. 1992, Oscarsson and Said 2012, Said et al. 2012) Cores were tested at different temperatures and frequencies using the asphalt shear box (Said et al. 2011).

4. Structure and materials

To study the influence of heavy vehicle loading on rut formation in asphalt concrete layers, a full-scale road section was chosen. It is a common flexible pavement structure according to Swedish norms, i.e. gravel-bitumen pavement. The road section (part of the E6 motorway), shown in Figure 3, was chosen for evaluation and validation of the predictive model (validation is not included in this paper). It consists of a 40 mm conventional wearing course type SMA16 and a 195 mm layer of a typical roadbase mix called AG22 160-220. The roadbase thickness adopted for the road sections is somewhat thicker than a typical roadbase layer in Swedish pavements. The asphalt mixture recipes and the results from quality control of the bituminous layers during construction are reported in Ulmgren and Lundström (2006). Roadbase mix AG22 pen 160/220 has a binder content of 4.2% and an air void content of 5.2%. The aggregate type is quartzite with 100% crushed aggregate. Further details are reported in Ulmgren and Lundström (2006) and Said and Hakim (2009). Several specimens

were cored from asphalt concrete layers. The specimens were subjected to sweep test analysis, mentioned above, to determine the asphalt concrete viscosity needed to estimate rut depth using PEDRO model.
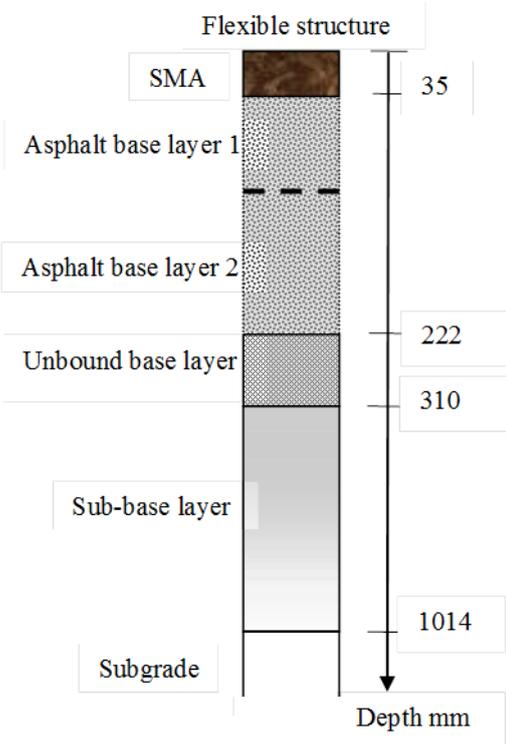

Figure 3 - Pavement structure

5. Influence of Traffic Variables

A sensitivity analysis of traffic variables for rut formation using the PEDRO model was performed under various loading conditions. Rut depth was calculated from horizontal line to maximum rut depth (the effect of upheaval on the total rut depth is not included here) for the pavement structure described above. The deformation in the wearing course was not included in this work to limit the number of calculations and since it does not influence the relative comparisons of traffic variables that were made. All estimations are illustrated relative to calculated deformation for an axle load of 100 kN, a dual-wheel configuration with a tire pressure of 0.8 MPa, traffic speed of 90 km/h, lateral wander of traffic with a standard deviation of 0.25 m, and at a temperature of 20°C unless specifically stated otherwise. The

influence of traffic variables; traffic speed, axle load, axle configuration (dual- and wide single-wheel tire), contact pressure and lateral wander on rut formation has been discussed.

5.1 Influence of Axle Load

The impact of axle load on rut formation is illustrated in Figure 4. Increasing axle load from 100 kN to 130 kN results in 23% more deformation in the asphalt concrete layer evaluated in this work. Investigation with different structures and materials and under different loading conditions might result in somewhat different relationships (Corté et al. 1994). Further studies would therefore be valuable.
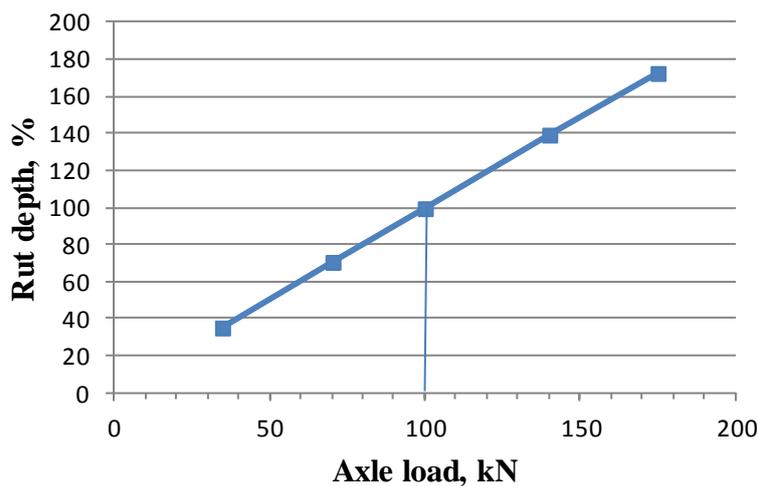

Figure 4 - Impact of axle load on rut depth formation in asphalt concrete layer relative to an axle load of 100 kN

5.2 Influence of Tire Pressure

According to this work the influence of tire pressure on rut formation is moderate, as shown in Figure 5. Increasing the tire contact pressure from 0.8 MPa to 1.0 MPa results in only 5 % more deformation. However, the type of asphalt concrete layer might have a significant influence on rut formation in respect of tire pressure as shown in Figure 6 (Said 2004). Further investigations are needed to clarify the effect of tire pressure in relation to various factors such as material type and traffic parameters at different temperatures.
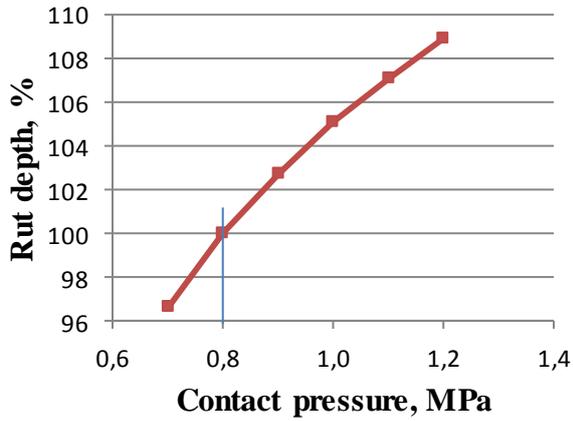
Figure 5 - Influence of tire pressure on rut formation at different axle load relative to an axle load of 100 kN with tire pressure of 0.8 MPa
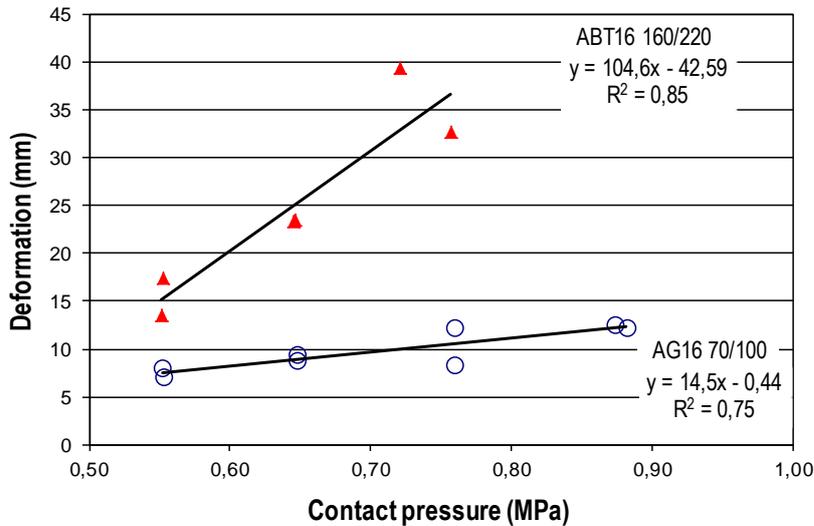
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Figure 6 - Influence of contact pressure on rut deformation in relation to different mixes

5.3 Influence of traffic speed

The influence of traffic speed as estimated by PEDRO is illustrated in Figure 7. The increase in rut depth is in inverse proportion to the traffic speed with less influence as speed increases. (Corté et al. 1994) reported decreases in rut depth of 5–30% when the loading speed increases from 38 km/h to 48 km/h depending on pavement structure and asphalt concrete materials.

According to the PEDRO package the corresponding change in rut depth is 26% for the tested structure, which is about the same.
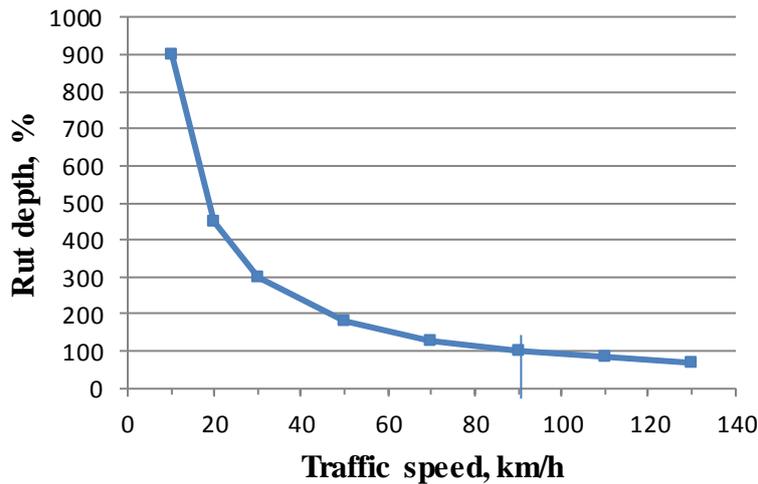

Figure 7 - Influence of traffic speed on rut formation

5.4 Lateral Wander

In the second stage the deformation is primarily related to the lateral movement of the material, which is induced by repeated shear stresses from heavy vehicle loading. This generates a depression under the wheel load and upheaval along the wheel path, as noted above. To calculate rutting under wheel load it is therefore crucial to include the effect of lateral wander. (Said et al. 2011) reported that the lateral distribution, with a standard deviation of 0.123 m, results in about 38 % less rut depth compared to if all the wheel passages loaded only the rut centre based on calculation using the PEDRO approach. Therefore, the influence of lateral wander of heavy vehicles cannot be omitted when predicting rut formation in pavement surfaces. Figure 8 shows the influence of standard deviations of traffic on the rut profile for dual-wheels. The rut depth at the centre of the wheel path and the upheavals along it increase with decreasing standard deviations of the lateral wander. The upheaval effect is obvious at standard deviations less than 0.35 m, which also increases the rut depth due to upheaval. Figure 9 shows rut development at different standard deviations of lateral wander of dual and single-wheels as a percentage of a standard deviation of 0.25 m. Decreasing the standard deviation from 0.25 m to 0.20 m for a dual-wheel results in a 16% increase in rut depth and at a standard deviation of 0.45 m results approximately half the rut depth compared to the standard deviation of 0.25 m. The influence of a wide single-wheel is even larger.

The idea behind the 2+1 lane road design, called "Collision-free-roads", planned and implemented by The Swedish Transport Administration (STA) since 1998 was to increase

traffic safety (Carlsson 2009). As 2+1 roads have narrow lanes and more channelized traffic, ruts develop faster, specifically on 1-lane sections results. The standard deviations of the lateral wander of the heavy traffic on 2-lanes and 1-lane sections are about 0.29 m and 0.24 m respectively for road RV34 (McGarvey 2012). This results in approximately 20% deeper rutting on the 1-lane section than on the 2-lanes section using the PEDRO. This is comparable to the measurements reported by Carlsson (2009) with increasing rut depths due to heavy traffic (80 % of the total rut depth) on the 1-lane sections of 23%–52% of the rut depths on the 2-lanes sections depending on the pavement structures and traffic volume.
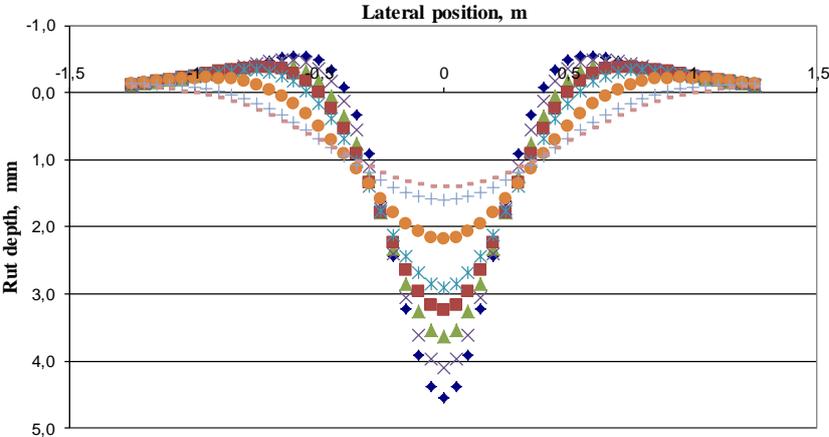

Figure 8 - Estimated rut profiles in relation to lateral wander at different standard deviations of a wide base wheel load
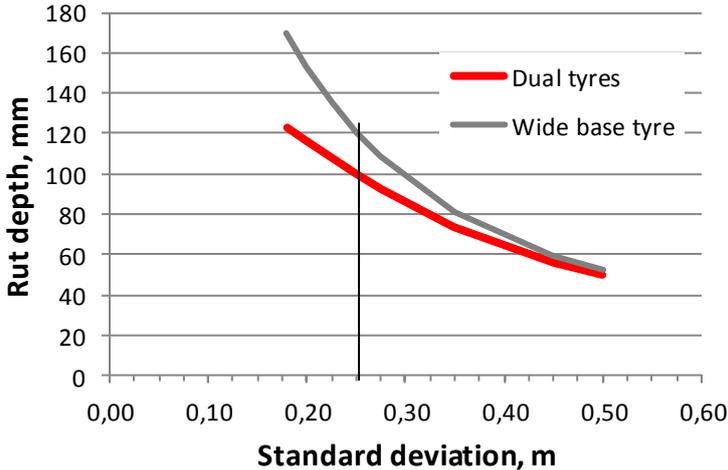

Figure 9 - Influence of standard deviations on rut development

5.5 Influence of wide single-wheel

In Figure 10, the wide single-wheel is shown to be more aggressive as regards rut damage, as expected. Taking into consideration the effect of lateral wander, shown in Figure 9, the rut depths ratio varies in this study from 1.05 to 1.40. Note that this ratio may be different for different materials; however the range of the ratio is comparable to the ranges reported by (Corté et al. 1994) in the case of full-scale accelerated loading.
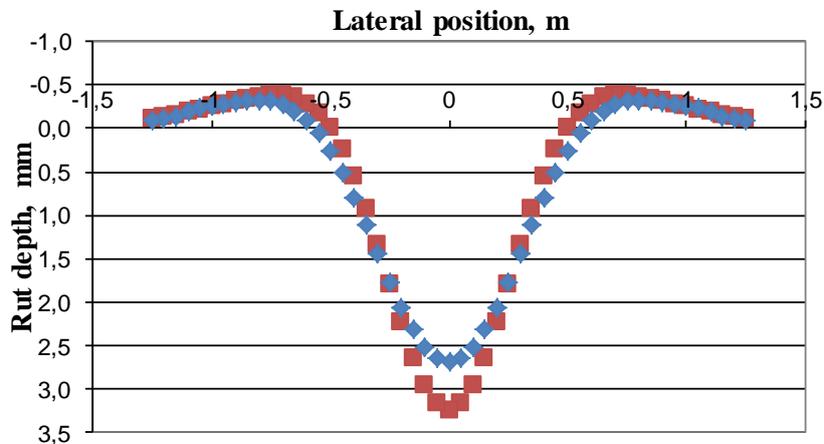

Figure 10 - Comparison of the rut depths between wide single and dual wheel load.

5.6 Equivalent axle load (4th power law)

It is practical to use a rutting factor to estimate rutting caused by different wheel loads. A widely used fourth power law relating pavement damage to the applied wheel load was evaluated in this work. However, the exponent value of four has been in question (OECD, 1991). Several years' traffic data from a weight-in-motion system (Winnerholt and Larsson, 2010) has been used to evaluate the 4th power law in respect of rutting damage. The axle load measurements result in 14 classes of +/- 5 kN intervals for axle loads heavier than 35 kN. Shorter intervals, for example +/- 2.5 kN, would be more appropriate and further investigation will be valuable to determine suitable intervals. Table 1 shows a summary of measurements performed over one week at Kungsbacka station. The number of equivalent standard axle loads (100 kN), calculated according to the fourth power law, was 1696 ESALs. The rutting in the pavement structure was calculated based on the number of ESALs and the sum of rutting developed from the axle load classes. Figure 11 indicates that the rut depth predicted in respect of estimated number of equivalent standard axle loads (ESALs) is about half the rut depth based on actual axle load measurements. Note that to be more accurate the comparison should be made after calibration of the PEDRO model with experimental or field measurements. This relationship might also be different for different structures and testing conditions and, therefore, further investigations would be valuable.

Table 1 - Measured axle loads data from WIM system, Kungsbacka station.

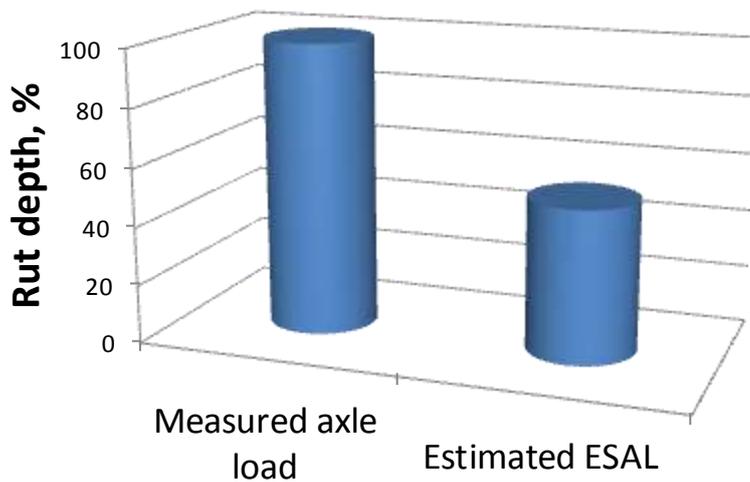| Axle load classes, kN	No. of axle loads per day	No. of ESALs
40	722	18
50	802	50
60	1063	138
70	988	237
80	599	245
90	358	235
100	203	203
110	129	188
120	84	174
130	39	113
140	12	47
150	5	26
160	2	15
170	1	7
Total no. of ESALs		1696

Figure 11 - Influence of estimated ESAL on rut development in relation to rut depth based on measured axle loads

6. Conclusions

In summary, it is noted that the PEDRO approach is an outstanding tool for analysis of traffic variables in respect of rutting in the asphalt concrete layers. The approach is also valuable for studying the performance of the pavement structures under various temperature conditions in respect of resistance of asphalt concrete layers to rutting. The influence of traffic variables on rut formation in asphalt concrete layers has shown reasonable indications as it could be recognized based on best practice. On the other hand, for practical use the approach needs to be calibrated with the actual field conditions with respect to different pavement structures and at a range of traffic loads under various climatic conditions.

7. References

- Björklund, A. (1984). Creep Induced Behaviour of Resurfaced Pavements. inköping, Sweden, Swedish Road and Transport Research Institute.
- Blab, R. and Harvey, J. T. (2002). Viscoelastic rutting modelwith improved loading assumptions. 9th International Conference on Asphalt Pavements, The Danish Road Directorate, Copenhagen, Denmark.
- Carlsson, A. (2009). Uppföljning av mötesfria vägar. VTI rapport 636-2009. Linköping, Sweden.
- Collop, A. C., Cebon, D. and Hardy, M. S. A. (1992). A Visco-Elastic Approach to Rutting in Flexible Pavements, Cambridge University Engineering. Cambridge, UK.
- Corté, J.-F., Brosseaud, Y., Simoncelli J-P. and Caroff, G. (1994). "Investigation of rutting of asphalt surface layers: influence of binder and axle loading configuration." Transportation Research Record 1436: 28-37.
- Eisenmann, J. and Hilmer, A. (1987). Influence of Wheel load and Inflation Pressure on the Rutting Effect of Asphalt Pavements - Experiments and Theoretical Investigations. 6th Int. Conf. on the Structural Design of Asphalt Pavements, The University of Michigan, Ann Arbor, USA.
- Hopman, P. C. and Nilsson, R. N. (2000). COMPASS; to design functional mixes. 1st International Conference, world of Asphalt Pavement, Sydney.
- Kaloush, K. E. and Witczak, M. W. (2002). "Tertiary flow characteristics of asphalt mixtures". Journal of the Association of Asphalt Paving Technologists 71: 248-280.
- McGarvey, T. (2012). 2+1 vägar med bredning av väg. Linköping, VTI. Unpublished.
- OECD (1991). Full-scale pavement test. Paris, OECD, Paris.
- Oscarsson, E. and Said, S. F. (2012). "Assessment of Zero Shear Rate Viscosity in asphalt Concrete using Shear Frequency Sweep Testing", Materials in Civil Engineering Retrieved February 2012, http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0000503
- Said, S. F. (2004). Prediction of Flow Rutting. International Symposium on Design and Construction of Long Lasting Asphalt Pavements, International society for Asphalt Pavements, Auburn, USA.

- Said, S. F. and Hakim, H. (2009). Performance evaluation of fatigue cracking in flexible pavement. CD-ROM, Transportation Research Board, Washington D.C.
- Said, S. F., Hakim, H. and Eriksson, O. (2012). Rheological characterization of asphalt concrete using a shear box. Linköping, VTI. Unpublished.
- Said, S. F., Hakim, H., Oscarsson, E. and Hjort, M. (2011). "Prediction of Flow Rutting in Asphalt Concrete Layers" International Journal of Pavement Engineering 12:6, 519-532.
- Sebaaly, P. E. (1998). Determination of Pavement Damage from Super-Single and singled-out Dual Truck Tires. NCHRP 1-36, National cooperative Highway Research Program.
- Sousa, J. B., Craus, J. and Monismith, C. L. (1991). Summary Report on Permanent deformation in Asphalt Concrete., Institute of Transportation Studies, University of California, Berkeley, USA.
- Ulmgren, N. and Lundström, R. (2006). The SMA principle applied to wearing, binder and base course layers - the Viaco Concept. 10th International Conference on asphalt pavements, Québec, ISAP.
- Verstraeten, J. (1995). Bituminous materials with a high resistance to flow rutting. Paris, France, World Road Association, PIARC Technical Committee on Flexible Roads.
- Winnerholt, T. and Persson, L. (2010). Results from 6 years of Swedish measurements with bridge WIM systems during 2004-2009. International heavy vehicle symposium, Melbourne, Australia.