INFLUENCE OF HEAVY TRAFFIC LATERAL WANDER ON PAVEMENT DETERIORATION

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ABSTRACT

Lateral wander of the traffic has an impact on the degradation development of pavements. This is usually not accounted for in the structural design process. Facilities with wide carriageways and broad shoulders tends to have relatively large lateral spreading while narrow road facilities lacking any shoulders can have highly channelized traffic pattern. In this research lateral wander characteristics have been measured for different road facilities. They can be assumed follow a normal distribution where the standard deviation describes their lateral spreading. Rut depth has thereafter been estimated according to two new rutting calculation scheme where lateral wander characteristics has been taken into account. The first approach is based on a two step mechanistic empirical (M-E) evaluation of the permanent strain in all layer of the structure and using a time hardening approach to sum up for all wander locations. This has thereafter been used to estimate the difference in rutting development as a function of the standard deviation. The second approach concentrates on calculating the permanent strain visco-elastically in the bound layers of the structure. Both procedures can be used to estimate the rate of relative deterioration for different road facilities. Based on the same structure the first approach give around 6 % increase in the surface rut as the standard deviation of the lateral wander increases from 10 to 20 cm. The second approach estimates this difference to be around 20 %. The difference between the two approaches are partly explained due to that the first approach estimates the rut based on all layers but the second approach from the bound layers only.

1 INTRODUCTION

Lateral wander of the traffic has an impact on the degradation development of pavements. This is usually not accounted for in the structural design process although it is known that wider wander prolongs the design life of the structure. The influence of the wander on the design life is complex and the pavement community does not have good method to quantify the impact of different wander distribution. Different pavement facilities have different wander characteristics. Facilities with wide carriageways and broad shoulders tends to have relatively large lateral spreading while narrow road facilities lacking any shoulders can have highly channelized traffic pattern.

A system to measure the lateral distribution of the traffic has been developed by VTI (The National Road and Transport Research Institute) in Sweden. The system is based on utilization three coaxial cables that are glued to create Z form on the pavement surface. As a tyre hits the three cables a triboelectrical interaction is induced that can be used to locate the tyre laterally.

Rutting is a common distress mode of pavement structures. Rutting, as it manifests on the surface, is a contribution of accumulation of permanent deformation within the pavement structure. Dependent on the pavement structure, layer thicknesses and material characteristics, all layers can contribute.

A common road structures in Sweden, usually referred 2+1 roads as there are three lane roads consisting of two lanes in one direction and one lane in the other whereof the directions are alternating every few kilometres. The two directions are usually separated using a light steel cable barrier. These roads have almost the same safety as motorways but are much cheaper to build. As 2+1 roads are narrower than normal dual carriageway, they have different lateral wander characteristics and thus their distress development is affected.

To get a better idea of the lateral wander effect on the degradation rate a simple procedure to calculate the rutting accumulation has been developed that takes into account the lateral wander. The procedure is based on a mechanistic-empirical (M-E) approach were the accumulation of the rutting is carried out according a time hardening scheme using a simple work hardening models for each pavement layer. This procedure has been used to estimate the rutting development for different lateral wander distributions.

2 LATERAL WANDER OF TRAFFIC LOADING

VTI developed in the early 1980´s a system to measure accurately the lateral position of passing vehicles (tyres). The system uses three coaxial cables that are glued in a Z form on the road surface as shown in Figure 1 and 2. The three cables are named start, diagonal and stop cables, respectively. The distance between the start and stop cable is 5.0 metres. The diagonal cable is angled 45° with respect to the start cable.

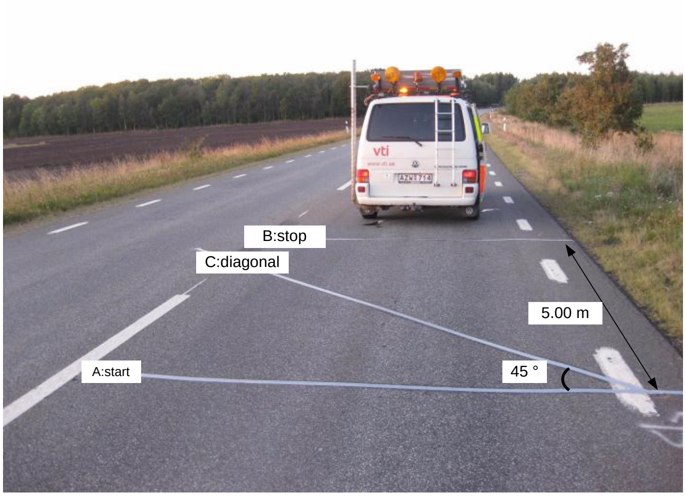

Figure 1. The setup of the system used to measure the lateral position of vehicles.

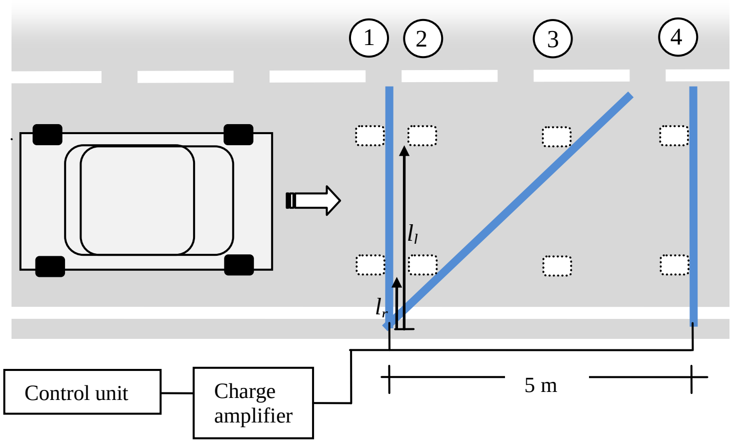

Figure 2. Schematic overview of the lateral position measuring system.

As a tyre hits one of the cables a triboelectrical interaction effect is induced (a charge is initiated through wear between inner conductor and the dielectric insulator) and an electronic charge movement is created in the cable centre core. This charge is then amplified and changed into a voltage pulse. The time as the voltage pulse enters the traffic analyser is thereafter registered.

For each passing axle the following times are registered:

- t_A: time as the tyre (axle) hits the start cable (1).
- t_{CH}: time as the right tyre hits the diagonal cable (2).
- t_{CV}: time as the left tyre hits the diagonal cable (3).
- t_B: time as the tyre (axle) hits the stop cable (4).

The axle speed v is calculated based on:

$$v = \frac{5.0}{(t_B - t_A)}$$

All axles within a defined time interval (user specified) and have the same speed are assumed linked to the same vehicle. The location of the right corner of the right and left tyre, respectively can now be estimated from:

$$l_r = 5.0 \cdot \frac{(t_{CH} - t_A)}{(t_B - t_A)}$$

$$l_l = 5.0 \cdot \frac{(t_{CV} - t_A)}{(t_B - t_A)}$$

3 2+1 ROAD DESIGN

A common road structures in Sweden usually referred 2+1 roads as they are three lane roads consisting of two lanes in one direction and one lane in the other whereof the directions are alternating every few kilometres. The two directions are usually separated using a light steel cable barrier. Roads of at least 13 m width can be converted to 2+1. With this the roads reach near motorway safety at much lower cost compared to traditional conversion to dual carriageway facilities. As 2+1 roads are narrower than normal dual carriageways this affects the driving behaviour including the lateral wander of the heavy traffic, thus rutting or distress development is affected. Two sections on a typical 2+1 road structure are shown in Figure 3.

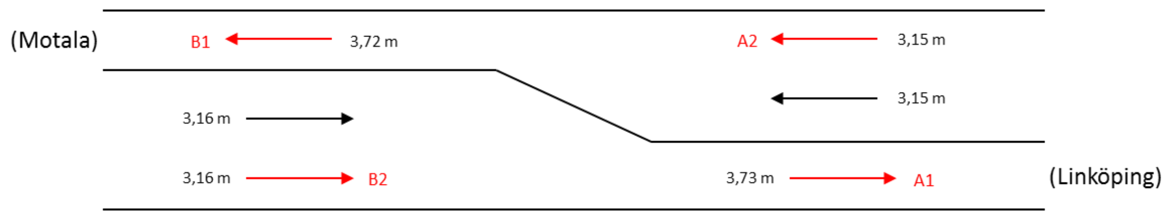

Figure 3. Lane widths and traffic directions at Road Rv34 of type 2+1 road in Southern Sweden, per each section.

The two flexible pavement sections, A and B at a Road Rv34 of type 2+1 road, are at opposite directions of traffic as described in Figure 3. The traffic wander has been measured at the right (outer) lanes in both directions. The results are given in Figure 4.

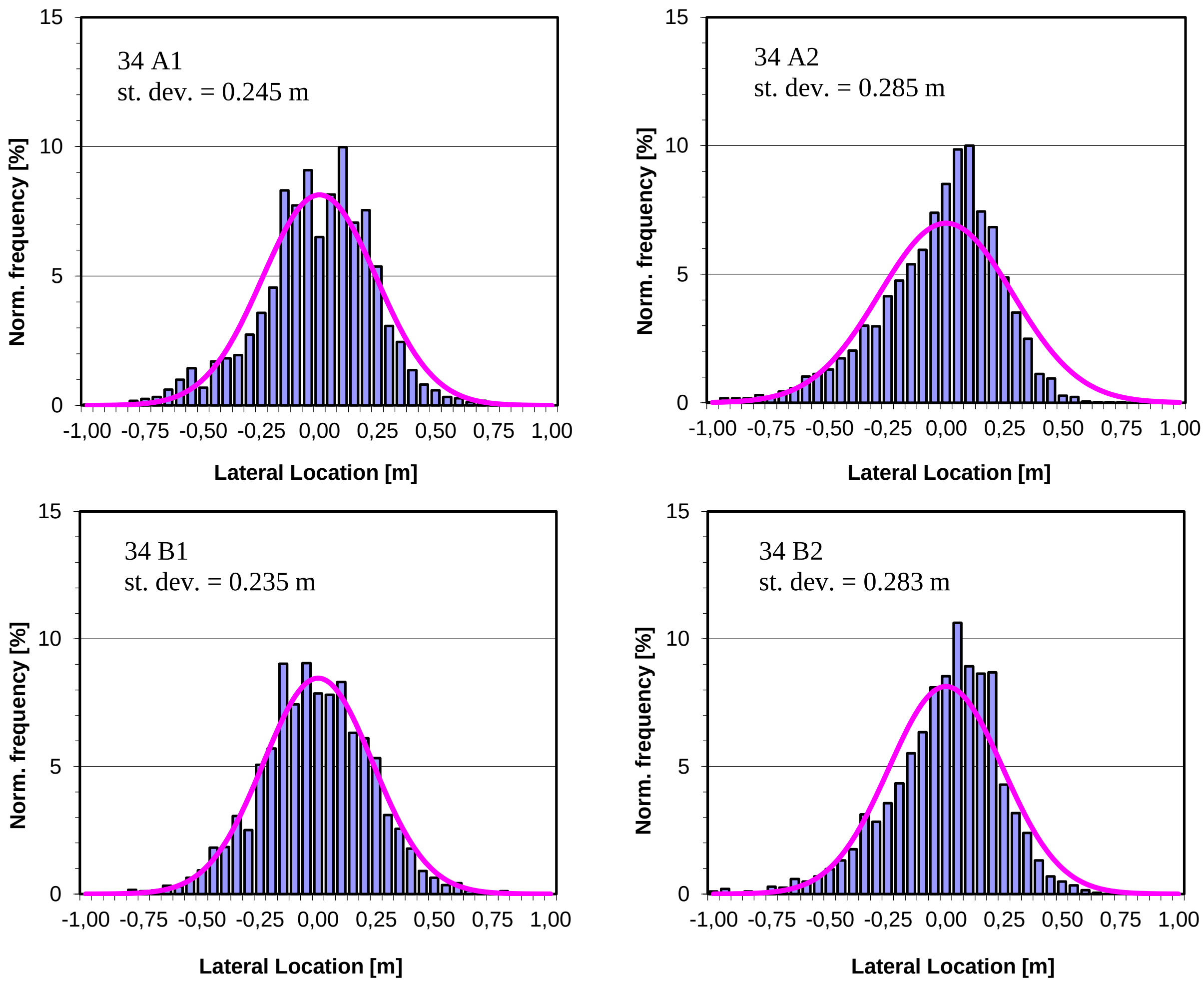

Figure 4. Normalized frequency of the lateral location of the heavy vehicles right wheel position on the arterial road Rv34 along with a normal distribution approximation. The mean value has been adjusted to zero and the standard deviation is given in the figures. A1 and B1 represent measurements on the single lane section of the road whereof the A2 and B2 are on the outer wheel lane of the two lane section.

Figure 4 shows the normalized lateral distribution of wheel load at lanes of different sections of the Road Rv34. Only the heavy traffic is shown. The distribution can be assumed normally distributed and by adjusting the mean values to zero (zero represents therefore the middle of the wheel path) the width of the distribution is represented by the standard deviation. The theoretical distribution curve is given as well on the figure.
The lateral variations in each lane are presented in standard deviations. It should be noted from Figure 4 that the standard deviations of the 1-lane road sections (A1 and B1) are less than the 2-lane sections (A2 and B2) in spite of wider lane widths of the 1-lane sections.

4 PAVEMENT STRUCTURE

In this work the pavement structures are, assumed, to consist of a standard flexible pavement structure according to Swedish norms. The speed limit, 90 km/h and all the loading consists of 100 kN standard single axle load configuration with dual tyres with inflation pressure 800 kPa with a c/c spacing of 34 cm. Further it is assumed that all the heavy vehicles traffic per direction are following the right lanes of sections A2 and B2 (Figure 3).
The layer thicknesses and elastic material characteristics of all layers are given in Table 1.

Table 1. Layer thicknesses and elastic material characteristics of the standard pavement structure.

Layer	Thickness h [mm]	Stiffness E / M_r [MPa]	Poissons ratio ν [-]
Asphalt Concrete	68	6500	0.35
Unbound Base Course	100	300	0.35
Subbase	500	160	0.35
Subgrade	-	100	0.35

The object used to estimate the impact of lateral wander on the rutting development has been measured to have a traffic loading consists of = 243 thousand single axle dual wheel standard axles (100 kN axle load and 800 kPa tyre pressure) per year with insignificant traffic increase during the analysis period. For simplicity the climate is considered constant during the year (T = 10°C). The traffic is assumed to vary in the lateral direction according to a normal distribution with a specific standard deviation.

5 PERMANENT DEFORMATION PREDICTION

As an attempt to estimate the influence of the lateral wander on the development on the rutting development two approaches have estimated. The first approach is refereed here as a two step mechanistic – empirical (M-E) (Erlingsson, 2012) and the latter as a visco-elastic approach (Said et al., 2011). They are briefly described next.

5.1 Simple M-E approach

The rut manifested on the surface is calculated by accumulation of the permanent deformation $\hat{\delta}_p$ in each layer with depth according to:

$$\hat{\delta}_p(N) = \int f(y)\left(\sum_{i=1}^{n}\sum_{j=1}^{m}\varepsilon_{p_{ij}}(y,N)\cdot\Delta z_{ij}\right)dy \tag{1}$$

where ε_p is the accumulate permanent strain at wander location y and function of the applied number of load repetitions N, $f(y)$ is the frequency of applied traffic loading at each wander location and Δz is thickness and each bound layer j is divided into i sub-layers.

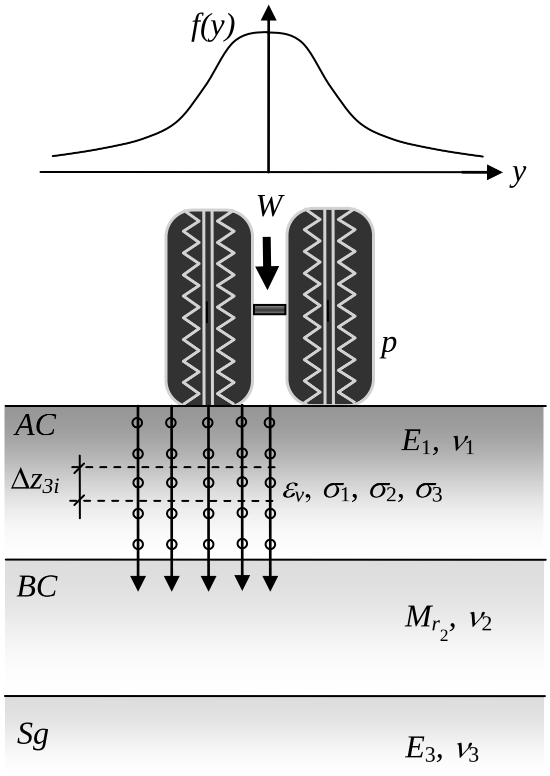

Figure 5. Schematic overview of the applied procedure to calculate the rutting. The asphalt concrete (AC) is divided into sublayers whereof the response is calculated in the middle point at desired lateral location. BC is the underlying granular base course resting on a subgrade (Sg).

The approach to extension of the method where each layer j is divided into i sublayers and the rut manifested on the surface is calculated by accumulation of the permanent deformation $\hat{\delta}_p$ in each layer with depth according to:

$$\hat{\delta}_p = \sum_{i=1}^{n}\sum_{j=1}^{m}\hat{\varepsilon}_{p_{ij}} \cdot \Delta z_{ij} \tag{2}$$

where $\hat{\varepsilon}_{p_{ij}}$ and Δz_{ij} are the average plastic strain and thickness of the ith sublayer of layer j, respectively, n is the total number of layers and j is the total number of sublayers of each layer. The bound layers, unbound aggregate layers (base course and subbase) and the subgrade were all modelled using different approaches.

Asphalt concrete

For the two layers of AC, a model dependent on temperature and number of load cycles is used where the accumulated strain is given as (ARA, 2004):

$$\frac{\hat{\varepsilon}_p(N)}{\Delta\varepsilon_r} = a_1 \cdot T^{a_2} \cdot N^b \tag{3}$$

where N is here the accumulated number of standard axles and T is the temperature in degrees centigrade, and a_1, a_2 and b are material parameters determined in the laboratory. The evaluation of the plastic strains according to equation (11) is carried out within a reference framework (i.e. in a laboratory test) giving the model parameters and thereafter scaled to represent the accumulation of plastic strain under the actual field conditions according to Tseng and Lytton (1989):

$$\frac{\hat{\varepsilon}_p^{field}(N)}{\Delta\varepsilon_r^{field}} = \frac{\hat{\varepsilon}_p^{lab}(N)}{\Delta\varepsilon_r^{lab}} \tag{4}$$

where *lab* and *field* denote the reference framework (lab) and the actual field conditions, respectively (Erlingsson, 2010). The model for the asphalt concrete is therefore given as:

$$\hat{\varepsilon}_p^{field}(N) = \frac{a_1}{\Delta\varepsilon_r^{lab}} \cdot T^{a_2} \cdot N^b \cdot \Delta\varepsilon_r^{field} = a_1^* \cdot T^{a_2} \cdot N^b \cdot \Delta\varepsilon_r^{field} \tag{5}$$

<u>*Base course and subbase*</u>

For the unbound aggregate layers a simple work hardening model (Korkiala-Tanttu, 2005 & 2008) is used. The model is given as:

$$\hat{\varepsilon}_p^{field}(N) = C \cdot N^b \cdot \frac{R}{A - R} \tag{6}$$

where C and b are material parameters, A is a parameter independent of the material (A = 1.05) and R is the deviatoric stress ratio defined as:

$$R = \frac{q_{\max}}{q_f} = \frac{q_{\max}}{s + mp_{\max}}$$

and

$$m = \frac{6\sin\phi}{3 - \sin\phi} \qquad \text{and} \qquad s = \frac{6c\cos\phi}{3 - \sin\phi}$$

where the cohesion c and angle of internal friction ϕ are based on static triaxial testing of the material.

<u>*Subgrade*</u>

The development of the permanent deformation in the subgrade is assumed to follow the Tseng and Lytton model (1989) given as:

$$\frac{\hat{\varepsilon}_p(N)}{\Delta\varepsilon_r} = \varepsilon_0 \cdot e^{-\left(\frac{\rho}{N}\right)^b} \tag{7}$$

where ε_0, ρ and b are material dependent regression parameters.

The model is thereafter scaled in a similar way as for the asphalt concrete to represent the actual field conditions. It is further assumed that the subgrade extends to great depth and that the induced resilient strain by the traffic loading decreases exponentially with depth

The procedure for adding together the permanent strain contributions in each sublayer follows the hardening principle (Lytton et al., 1993; Hu et al., 2011). This allows for an addition of contribution of permanent strains due to effects of different stress magnitudes resulting from various axle loads and environmental conditions. This can be expressed for the j:te step in the procedure where ΔN load repetitions of same stress magnitudes are applied as:

$$\hat{\varepsilon}_{p_j} = \hat{\varepsilon}_{p_{j-1}} + \hat{\varepsilon}_{p_j}(N=1) \cdot \left[\left(N_{eq_j} + \Delta N\right)^b - N_{eq_j}^b \right] \tag{8}$$

where N_{eq_j} is the equivalent total number of load repetitions at the beginning of the *j*:te load step defined as:

$$N_{eq_j} = \left[\frac{\hat{\varepsilon}_{p_{j-1}}}{\hat{\varepsilon}_{p_j}(N=1)} \right]^{\frac{1}{b}} \tag{9}$$

where *b* is the rate of change of the accumulation of permanent strain as defined in equations (13), (15), (16) and (17). The term $\hat{\varepsilon}_{p_j}(N=1)$ is further evaluated from the same equations after one load application ($N = 1$) only.

5.2 The visco-elastic approach

The second approach uses a visco-elastic model called PEDRO (Said et al., 2011). 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:

$$\varepsilon_p = \frac{\sigma_0 \cdot (1-2\nu)}{V \cdot \eta_A} \cdot \mathrm{Re}\left[\sqrt{(z+ix)^2 + a^2} - (z+ix) \right] + \frac{\sigma_0 \cdot z}{V \cdot \eta_A} \cdot \mathrm{Re}\left[1 - \frac{z+ix}{\sqrt{(z+ix)^2 + a^2}} \right] \tag{10}$$

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 model consists of two terms: one for calculation of compressibility representing the initial zone when a substantial change in volume is expected, and one for calculation of the flow rutting part of the deformation when 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 layer or layers with respect of number of load applications.

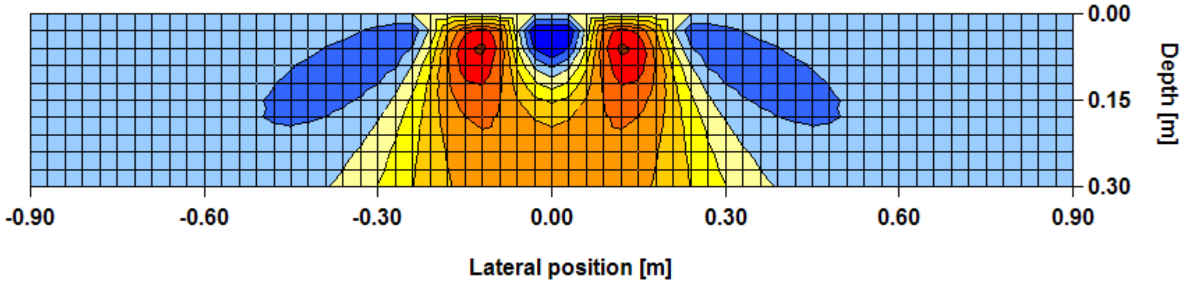

Figure 6. Distribution of the vertical permanent strain under dual wheel load (Oscarsson 2011).

6 RESULTS

Based on the above described M-E procedure rutting has been evaluated for the pavement structure for different lateral wander profiles. The results are shown on Figure 7 as the relative rut and have been normalized against the maximum rut at zero standard deviation.

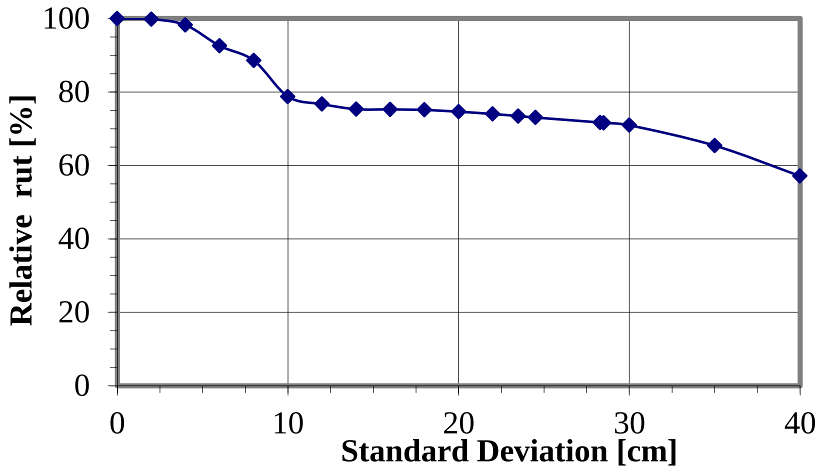

Figure 7. Relative surface rut as a function of the standard deviation of the lateral wander. The values are normalized against the maximum rut at zero standard deviation.

From Figure 7 is can been seen that the standard deviation has some influence on the rutting development of the structure. A narrow road facility with highly channelized traffic flow with a standard deviation σ_x < 10 cm show about 20% faster rutting development compared to a wide road facility

The visco-elastic approach on the other hand was used to calculate the rutting development for two standard deviation values on a 1-lane and 2-lane sections respectively. The results are shown in Figure 8.

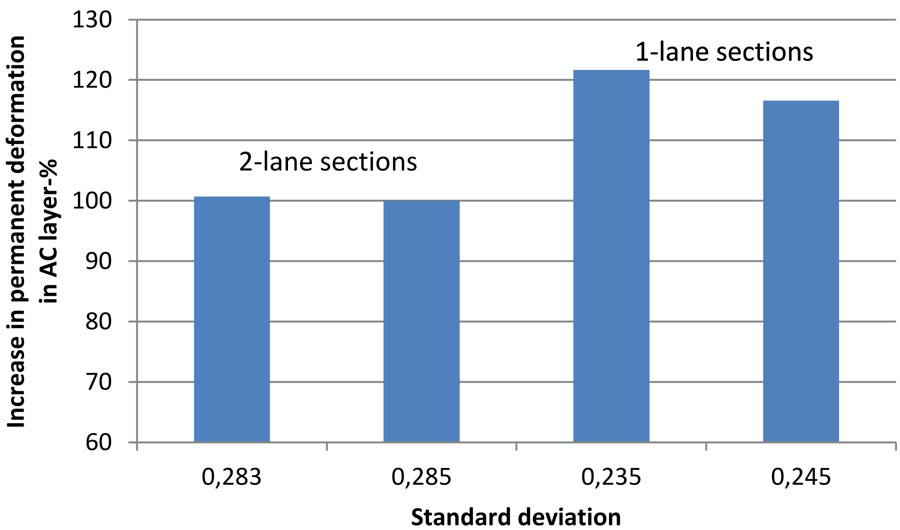

Figure 8. Increase in permanent deformation in bituminous pavement layer with respect of increase in standard deviations.

As can be seen in Figures 7 and 8 the two methods give a significant difference in their estimation of the lateral wander impact on the rate of rutting. According the first approach the impact from changing the lateral wander from 0.285 m to 0.235 is around 4-5% whereas the second approach estimates this difference to be around 20%. Part of the difference the two approaches may be due to that in the first approach the rutting calculation is based on plastic strain contribution from all layers of the pavement structure whereof in the latter approach only the bound layers are assumed contribute to the rutting.

7 CONCLUSIONS

Lateral wander of the traffic has an impact on the rutting development of pavements. This is usually not accounted for in the structural design. Rutting prediction was carried out for different lateral wander distributions by using two approaches for a specific test road section. The first procedure used was based on a two-step M-E approach whereof the latter approach was a visco-elastic approach.

The predicted differences using the first approach (ME approach) resulted in a 4-5 increase as the standard deviation of the lateral wander decreased from 0.285 m to 0.235 m. Using the visco-elastic approach about 20 % difference was observed. The large difference revealed by the two approaches needs further investigations. Wheel tracking tests are planned to calibrate the two approaches to give better agreement with field performances. It is the authors hope that in the future the influence of lateral wander of traffic will be considered as a parameter in the design process and included in a life cycle cost analysis.

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