Vehicle-Pavement Interaction

Parisa Khavasseefat

Doctoral Thesis
KTH Royal Institute of Technology
Engineering Sciences
Department of Transport Science
SE-100 44 Stockholm, Sweden
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Abstract

Several aspects of vehicle-pavement interaction have been studied and discussed in this thesis. Initially the pavement response is studied through a quasi-static and a dynamic computationally efficient framework under moving traffic loads. Subsequently, a non-stationary stochastic solution has been developed in order to account for the effect of pavement surface deterioration on pavement service life.

The quasi-static procedure is based on a superposition principle and is computationally favourable, as it requires only a reduced incremental problem to be solved numerically. Using the developed framework, the effect of vehicle configuration and traffic characteristics on the damage induced in pavements is investigated numerically. It is shown that the developed numerical model provides a more accurate explanation of different distress modes.

In the dynamic approach the pavement roughness and vehicle suspension system are linked to a dynamic pavement model in order to account for the dynamic effects of vehicle-pavement interaction on pavement response. A finite element method is employed in order to establish the response function for a linear viscoelastic pavement structure with dynamic effects taken into account. The developed computational procedure is applied to evaluate the effect of the pavement surface roughness on the pavement structure response to truck traffic loadings.

Furthermore, the deterioration trends for the flexible pavement surface have been investigated based on field measurements of longitudinal profiles in Sweden. A predictive function is proposed for surface deterioration that is based on the average gradient of yearly measurements of the road surface profiles in Swedish road network. The developed dynamic framework is further elaborated to a non-stationary stochastic approach. The response of the flexible pavement is given for a non-stationary random case as the pavement surface deteriorates in pavement service life, thus influencing the magnitude of the dynamic loads induced by the vehicles. The effect of pavement surface evolution on the stress state induced in the pavement by moving traffic is examined numerically.
Finally the effect of surface deterioration on pavement service life has been investigated and discussed in the thesis by incorporating the proposed prognostic surface deterioration model into a ME design framework. The results are discussed for different case studies with different traffic regimes. It was indicated that the predicted pavement service life decreases considerably when the extra dynamic loads, as a result of pavement surface deterioration, has been taken into account. Furthermore, the effect of performing a predictive rehabilitation process (i.e. resurfacing) has been studied by employing a LCC framework. The application of preventive maintenance was shown to be effective, especially when the deterioration rate is high.

**Keywords**

Finite element; Viscoelasticity; Moving load; Dynamic axle loads; Road roughness; Flexible pavement. Stochastic
Preface

The work for this thesis has been carried out at KTH Royal Institute of Technology. This thesis is based upon five publications which are appended at the end of the thesis. The financial support of the project has been by Swedish Road Administration (Trafikverket) and the work is supervised by Professor Björn Birgisson and Assistant Professor Denis Jelagin at the division of Highway and Railway Engineering.

I am grateful to all the people that have helped me during this work. In particular I would like to thank Trafikverket, the reference group in Friday meetings and my colleagues at KTH.

Stockholm, 2014
List of publications

This thesis consists of an extensive summary and five appended papers.

**Paper A**  

**Paper B**  

**Paper C**  

**Paper D**  

**Paper E**  

The papers were prepared in collaboration with co-authors. The author of this thesis was the main author of all the publications. The analyses performed for paper A to D were planned with the co-authors and conducted by the first author. In paper E the author of the thesis was responsible for surface simulation and incorporation of dynamic loads to design framework.
Additional publications

In addition to the appended papers the author of the thesis has been involved in following publications.

Khavassefat, P. and Kringos, N., *Heavy Duty Pavements in Europe*, TRB circular, in publication


### Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>Asphalt Concrete</td>
</tr>
<tr>
<td>COST</td>
<td>European Cooperation in Science and Technology</td>
</tr>
<tr>
<td>DLC</td>
<td>Dynamic Load Coefficient</td>
</tr>
<tr>
<td>ESAL</td>
<td>Equivalent Standard Axle Load</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Method</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>FRF</td>
<td>Frequency Response Function</td>
</tr>
<tr>
<td>HMA</td>
<td>Hot Mix Asphalt</td>
</tr>
<tr>
<td>IRI</td>
<td>International Roughness Index</td>
</tr>
<tr>
<td>ME</td>
<td>Mechanistic-Empirical</td>
</tr>
<tr>
<td>PSD</td>
<td>Power Spectral Density</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>STA</td>
<td>Swedish Transport Administration</td>
</tr>
<tr>
<td>VTI</td>
<td>Swedish National Road and Transport Research Institute</td>
</tr>
</tbody>
</table>
Notations

\( \sigma_{ij} \quad \text{Cauchy stress tensor} \)

\( G \quad \text{Shear modulus} \)

\( K \quad \text{Bulk modulus} \)

\( e_{ij} \quad \text{Deviatoric strain tensor} \)

\( \phi_{ij} \quad \text{Volumetric strain tensor} \)

\( \delta_{ij} \quad \text{Kronecker delta function} \)

\( S \quad \text{Space domain (} x, y, z \text{)} \)

\( F(.) \quad \text{Load description in the continuum media} \)

\( \tilde{G}_i \quad \text{Prony series parameter} \)

\( \tau_i^G \quad \text{Relaxation time in the Prony series} \)

\( G_0 \quad \text{Instantaneous shear modulus} \)

\( E(a/r) \quad \text{Complete elliptical integral of the second kind with modulus} \ a/r \)

\( K(a/r) \quad \text{Complete elliptical integral of the first kind with modulus} \ a/r \)

\( H(.) \quad \text{Heaviside function} \)

\( \Gamma(.) \quad \text{Gamma function} \)

\( |E^*| \quad \text{Dynamic Modulus} \)

\( T \quad \text{Temperature} \)

\( E' \quad \text{Storage Modulus} \)

\( E'' \quad \text{Loss Modulus} \)

\( f_s \quad \text{Correction factor regarding to current state of existing coating and cracks on the pavement} \)

\( f_d \quad \text{Correction factor regarding to moisture content of the subgrade material} \)

\( \varepsilon_i \quad \text{Horizontal tensile strain at the bottom of AC layer} \)

\( \varepsilon_v \quad \text{Vertical compressive strain on top of the subgrade} \)

\( \dot{\varepsilon}_p(t) \quad \text{Creep strain rate} \)

\( f \quad \text{Frequency} \)

\( \omega \quad \text{Angular frequency} \)
\( f(.) \) Response function
\( v \) Velocity
\( k_x \) Wavenumber in x direction
\( h_f(.) \) Vehicle response function
\( \xi(.) \) Surface roughness description
\( \nu \) Poisson ratio
\( \rho \) Density
\( R(.) \) Correlation function
\( S(.) \) Power spectral density
\( t_l \) Long-term time, expressed in years
\( E(.) \) Expectation
\( A(.) \) Displacement PSD gradient
\( \Omega \) Spatial angular frequency
\( C \) Cost of the activity
\( r \) Discount rate
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Chapter 1.

Introduction

1.1. Background

Almost half of the freight transport in Europe is done via road networks. Considering that freight transport is an essential component for the economic development of countries, a high quality road network is not only of great importance to the transport sector itself, but also is essential to all associated industries as well as the whole national economy. In Europe, there is currently an ongoing discussion on using longer and heavier vehicles for road freight transport to increase its capacity. A study by Swedish national road and transport research institute (VTI) indicated a decrease of 24% in cost of transport when replacing standard EU trucks with longer and heavier Swedish trucks (35% longer and 50% heavier) (Björketun, et al., 2008). However the opinions about the implication of this alternation are quite dispersed. In particular, the dynamic vehicle-pavement interaction becomes a more dominant cause of failure in pavements as the magnitude of the induced loads becomes significantly higher. The damaging effects of the vehicle-pavement interaction are in fact not well understood as they are considerably different from the load configuration used in the current state-of-practice design procedures.

In the majority of the current design and evaluation procedures for flexible pavements, linear elastic analysis is used to evaluate stresses and strains induced by traffic loadings in the structure. However, the analysis based on these assumptions may not provide accurate qualitative and quantitative description of the pavements mechanical behaviour. One of the important characteristics of asphalt pavements which is often neglected is viscoelasticity. The viscoelastic properties of asphalt play a crucial role in pavement response and performance, e.g. Pouget et al. (2010). As a result, analysis methods based on linear elasticity are unable
to predict several pavement distress modes observed in the field, i.e. top-down cracking and permanent deformation, cf. Ali et al. (2008), Wang et al. (2009), Liao and Sargrand (2010). Finite element (FE) modelling of pavement structures has been widely used e.g. (Elseifi et al., 2006; Arraigada et al., 2009; Pouget et al., 2010). The popularity of FE method is due to the evident advantage of the method in terms of its capability of taking into account various aspects of material behaviour (e.g. viscoelasticity; anisotropy), arbitrary geometry of the loaded areas and different types of loading and boundary conditions. Even though considering an accurate FE model with 3D geometry and realistic material behaviour are essential for capturing many distress types in pavement structures, it comes at the expense of much longer computation time.

The dynamic effect of vehicle-road interaction on the exerted loads on pavements is another important factor that has often been neglected in most of the state-of-practice design procedures. These effects are hardly negligible, especially with the increase of traffic weight and density in recent years, (cf. European Commission, 2008).

One of the main components of the dynamic vehicle-pavement interaction system, is pavement roughness. Pavement surface roughness can be regarded as a random process (e.g., Dodds and Robson, 1973). In general practice, the road surface irregularities are treated as a zero mean value stationary stochastic process (Lombaert et al., 2004; Sun and Kennedy, 2002). However, there are many evidences that pavement surface deteriorates during its service life due to various reasons (e.g. traffic, environment, etc.). Therefore the statistical characteristics of the surface roughness changes in time, which results in a non-stationary surface irregularity description. The rougher surface results in accelerated development of different crack types on the road surface (Liu et al., 2000; Liu, 2001). The deterioration of road surface during the road’s design life is an important factor to be considered as it results in higher surface roughness and thus in increase of dynamic loads exerted on the pavement and eventually shortening the pavement surface life.
1.2. Objectives

The main objective of this thesis is to study the dynamic aspects of vehicle road interaction in a numerical efficient way. The focus is to evaluate the dynamic pavement response to moving vehicles and study the effects of pavement surface deterioration on the dynamic pavement response and eventually on the pavement service life.
Chapter 2.

Pavement response to moving loads

Major components of the vehicle-road interaction mechanism are illustrated in Figure 1. The interaction of the vehicle suspension system with the pavement surface roughness generates dynamic loads on the pavement. The loads are transferred from the vehicle to the pavement through the tyres; the contact stresses on the pavement surface and the geometry of the loaded area are thus affected by the tyre type and inflation pressure. The stress-strain state induced in a pavement by the contact stresses on its surface is controlled by the geometry and mechanical properties of the pavement layers.

In this section two approaches of dealing with the problem of moving loads on the pavement are presented. Finite element analysis has been utilised for both approaches.

Figure 1: Mechanism of the vehicle-road interaction
2.1. Quasi-static approach

A quasi-static process is a slow process in which acceleration and inertial effects are neglected. In such a process, time becomes a parameter (artificial time) instead of an independent variable (Strang, 2007). The problem of moving loads on the pavement can be approximated by a quasi-static problem.

To analyse the pavement structure with this approach, initially the structural response to a single tyre is obtained, which loads and unloads the pavement. A loading history matrix \( F \) consisting of positive, negative and zero coefficients is then constructed. Zero coefficients indicate the areas whose loading conditions are not changed at a given time increment, positive coefficients indicate areas loaded at given time increment and the negative ones indicate areas being unloaded. This matrix contains all the information concerning the loading configuration and speed. Figure 2 illustrates the construction of the impulse matrix for an arbitrary axle configuration moving along the line parallel to the x coordinate.

\[
\sigma(F(S,t),x,y,z,t) = \text{ifft}(\text{fft}(F^*) \cdot \text{fft}(\sigma^*))
\]  

Figure 2 : Impulse matrix for a moving input

The response of the pavement to an arbitrary surface loading history may be obtained in a computationally favourable way through the equation below, provided that the pavement response \( \sigma \) to a unit load increment is known.
here $fft$ is the Fast Fourier transform operator and $ifft$ is the inverse Fast Fourier transform. $fft$ multiplication produces the cyclic convolution. To fix this, $N-1$ zeroes have to be added to $F$ and $\sigma$ so that cyclic and non-cyclic convolution involve the same multiplication, where $N$ is the size of the vectors. In equation (1) the asterisk sign returns the vectors extended by $N-1$ zeroes. More details on the derivation of equation (1) and how to obtain the pavement response to a unit load ($\sigma$) are given in Paper A. Using equation (1), one may obtain the response of a linear pavement structure to any arbitrary loading history.

### 2.2. Dynamic approach

When the pavement surface unevenness is considered, the result of vehicle interaction with an uneven surface is a dynamic process. Dynamic loads are generally assumed to increase the pavement damage by approximately 20 to 30% (Cebon, 1988). Therefore the dynamic effects of vehicle-road interaction have a significant influence on the stresses induced in asphalt layers. Thus the dynamic effects have to be taken into account to achieve accurate predictions of the pavement structures service life.

**Deterministic approach**

The dynamic response of the pavement system assuming that the pavement structure is comprised of materials with linear behaviour, e.g. linear viscoelastic layers, to mechanical loads can be calculated from the equation below, provided that the impulse response function is known:

$$
\tilde{f}(k_x,y,z,\omega) = \tilde{F}_x(k_x,y,z,\omega) \cdot \tilde{h}(k_x,y,z,\omega)
$$

(2)

In equation (2), $\tilde{h}(k_x,y,z,\omega)$ is the response function for the flexible pavement structure where $y$ and $z$ are spatial coordinates, $k_x$ is the wavenumber in $x$ direction, $\omega$ is the angular frequency, and $\tilde{F}_x(k_x,y,z,\omega)$ is the dynamic moving load induced from the vehicle on the pavement in frequency wavenumber. Assuming the load is moving along the $x$-axis on the surface, the load description in three-dimensional space with $t$ being time vector and $v$ the speed of moving vehicle can be presented as follows:

$$
F(x,y_0,z_0,t) = F_x(x - vt) \cdot F_y(y_0) \cdot F_z(z_0) \cdot F_t(t)
$$

(3)
Applying a double Fourier transform on equation (3), the load description in frequency-wavenumber domain is defined as (e.g., Lombaert et al., 2004):

\[
\tilde{F}(k_x, y_0, z_0, \omega) = F_y(y_0) \cdot F_z(z_0) \cdot \tilde{F}(k_x) \cdot \left[ \int_{-\infty}^{+\infty} F_i(t) \cdot e^{-i(\omega-k_x \cdot v) \cdot t} \, dt \right].
\]  

In equation (4) the bracket term is the frequency shifted Fourier transform of the time-dependent amplitude of the moving load (Lombaert and Degrande, 2001). Applying the shift in frequency domain and replacing equation (4) with equation (3), the response of the pavement to moving load can be written as:

\[
\tilde{f}(x, y, z, \omega) = \tilde{F}_x(k_x) \cdot \tilde{F}_i(\omega-k_x \cdot v) \cdot F_y(y_0) \cdot F_z(z_0) \cdot \tilde{h}(k_x, y, z, \omega)
\]

in which \( \tilde{F}_x(k_x) = \tilde{F}_x(\omega/v) \) is the load description in wavenumber domain and \( \tilde{F}_i(\omega-k_x \cdot v) \) is the frequency of moving load. The dynamic load is presented as below in a deterministic way, when the surface roughness, \( \xi(k_x) \), and the vehicle response function, \( h_j(k_x) \), are known:

\[
\tilde{F}(k_x, y_0, z_0, \omega) = h_j(k_x) \cdot \xi(k_x) \cdot F_y(y_0) \cdot F_z(z_0) \cdot \tilde{F}_i(\omega-k_x \cdot v)
\]

The reader is referred to Paper C for more details on the derivation of the equations and on how to obtain the vehicle and the pavement transfer functions.

**Stochastic approach**

Road surface roughness can be regarded as a random process (e.g., Dodds and Robson, 1973). Thus, the surface roughness is often defined by a power spectral density (PSD) in frequency or wavenumber domain and a stochastic approach may be used in order to analyse the pavement structure. In general practice, the road surface irregularities are treated as a zero mean value stationary stochastic process (Lombaert et al., 2004; Sun and Kennedy, 2002). A stationary process is a stochastic process where the statistical characteristics (e.g. mean and variance) are constant over time. However, it is evident that the road surface profile evolves in
time because of several different reasons, e.g. traffic and climate effects. Generally the pavement surface is smooth right after construction and it gets rougher during pavement service life which leads to higher magnitude of dynamic loads on the pavement. Therefore, as a result of pavement surface deterioration, non-stationary stochastic analysis is suitable for analysing pavement response to moving loads. More information on pavement surface deterioration is discussed in Chapter 3 of the thesis.

The non-stationary PSD of the response is given as follow in frequency-wavenumber domain:

\[
S_{yy}(k_{x1}, k_{x2}, \omega_1, \omega_2, t_{i1}, t_{i2}) = E[\tilde{f}^*(k_{x1}, \omega_1, t_{i1}) \tilde{f}(k_{x2}, \omega_2, t_{i2})]
\]

where the asterisk sign denotes the complex conjugate and \( t_i \) is a variable in long time scale expressed in years. Inserting equation (6) in equation (7) the PSD of the response may be written in an expanded form as below:

\[
S_{yy}(k_{x1}, k_{x2}, \omega_1, \omega_2, t_{i1}, t_{i2}) = h_f^*(k_{x1}) \cdot h_f(k_{x2}) \cdot \tilde{F}_t^*(\omega_1 - k_{x1} \nu) \cdot \tilde{F}_t(\omega_2 - k_{x2} \nu) \\
F_y(y_0) \cdot F_z(z_0) \cdot \tilde{h}^*(k_{x1}, \omega_1) \cdot \tilde{h}(k_{x2}, \omega_2) \cdot E[\tilde{\xi}^*(k_{x1}, t_{i1}) \cdot \tilde{\xi}(k_{x2}, t_{i2})]
\]

noting that \( \xi(k_x, t_i) \) is a non-stationary random process, equation (8) can be re-written as:

\[
S_{yy}(k_{x1}, k_{x2}, \omega_1, \omega_2, t_{i1}, t_{i2}) = h_f^*(k_{x1}) \cdot h_f(k_{x2}) \cdot \tilde{F}_t^*(\omega_1 - k_{x1} \nu) \cdot \tilde{F}_t(\omega_2 - k_{x2} \nu) \\
\cdot F_y(y_0) \cdot F_z(z_0) \cdot \tilde{h}^*(k_{x1}, \omega_1) \cdot \tilde{h}(k_{x2}, \omega_2) \cdot S_{\xi\xi}(k_{x1}, k_{x2}, t_{i1}, t_{i2})
\]

The formulation for obtaining the non-stationary response of flexible pavements to moving loads is presented and discussed thoroughly in paper D.

### 2.3. Numerical examples and results

Both the quasi-static and dynamic approaches are performed in order to analyse the pavement structure under moving loads. In the FE analyses, the pavement system is modelled as a multilayer system as depicted in Figure 3, with the first layer modelled as a linear viscoelastic layer, while the rest of the layers are considered to be homogeneous and elastic with
different stiffness. The properties of the pavement layers used in this thesis are listed in Table 1. The viscoelastic behaviour of the asphalt layer is assigned through a Prony series formulation of the shear relaxation modulus, represented with generalized Kelvin:

\[ g_R(t) = 1 - \sum_{i=1}^{N} \overline{g}_i^p \left(1 - e^{-\frac{t}{\tau_i^G}}\right) \]  

(10)

with \( \overline{g}_i^p \) and \( \tau_i^G \) are material constants; \( N \) is the number of terms in the Prony series expansion; and \( g_R(t) \) is a normalized shear relaxation modulus. The Prony series parameters used in the current thesis are listed in Table 2.

![Figure 3: Schematic view of a layered structure of a flexible pavement](image)

<table>
<thead>
<tr>
<th>Layer type</th>
<th>Thickness [mm]</th>
<th>Material Properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bituminous Layer</td>
<td>160</td>
<td>E [MPa] ( \nu ) ( \rho ) [kg/m³]</td>
<td>See Table 2 2200</td>
</tr>
<tr>
<td>Base Layer</td>
<td>150</td>
<td>450 0.35 2400</td>
<td></td>
</tr>
<tr>
<td>Sub-Base Layer</td>
<td>350</td>
<td>240 0.35 2400</td>
<td></td>
</tr>
<tr>
<td>Subgrade</td>
<td>Infinite</td>
<td>100 0.35 2400</td>
<td></td>
</tr>
</tbody>
</table>
Table 2: Prony series coefficients for defining viscoelastic behaviour of asphalt mixture

<table>
<thead>
<tr>
<th>$i$</th>
<th>$-p_i$</th>
<th>$g_i$</th>
<th>$\tau_i^G [s]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.13 e-1</td>
<td>1.70 e-1</td>
<td>1.75 e-1</td>
</tr>
<tr>
<td>2</td>
<td>1.47 e-2</td>
<td>5.03</td>
<td>1.14 e+2</td>
</tr>
<tr>
<td>3</td>
<td>8.44 e-2</td>
<td>2.72 e+5</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$G_o = 4740$ MPa

The effect of traffic speed and density on the stresses induced in the pavement is shown in Figure 4 as obtained with quasi-static analyses. In Figure 4, the maximum principal stresses induced at the pavement surface by passages of 6 different truck types with 15 meters interval are shown. In the figure, for a more clear visualization, the envelope over stress history has been shown on graphs, i.e. only points corresponding to the maximum stresses caused by the passage of each vehicle are selected. It can be observed in Figure 4 that the magnitude of residual tensile stresses increases with time. In general, vehicles with more axles cause more stress in the pavement as the rate of loading increases. Moreover, one may observe that an increase of the speed has different effect on induced stresses by different truck types. In this case, increasing the speed from 10 km/h to 45 km/h results in a 5% decrease of tensile stress level for a 2 axle truck, while changing the same parameters for a 6 axle truck leads to an increase of 6.5% in the level of surface tensile stresses. More results on quasi-static analyses are reported in Paper A and B.

Figure 4: Evolution of maximum principal stress on the surface of asphalt layer at passages of trucks with the speed of (a) 10 km/h and (b) 45 km/h
The dynamic effects at vehicle-road interaction are studied for the idealised pavement structure shown in Figure 3 with the properties listed in Table 1 and 2. The dynamic load induced on the pavement by a quarter car model representing a heavy vehicle is calculated for two different road roughness profiles. The first profile belongs to a fairly new and fairly even highway and the second profile belongs to a highway with a higher level of unevenness compared to the first road profile.

In Figure 6, the dynamic load induced by a quarter car vehicle model (as shown in Figure 5) over road profile 1 and 2 with a speed of 30 m/s is shown. The main visible peak at approximately 2 Hz corresponds to the main body bounce mode of vibration, while the resonance frequency for wheel hop is not visible in this figure as the level of the road excitation is very low at that range of frequencies (Cebon, 2000). One may see in Figure 6 that the maximum force amplitude from profile 2 is approximately 40% higher than the one from profile 1.

**Figure 5**: Quarter car model with 2 degrees of freedom

The pavement response from this type of analysis can be obtained in frequency-wavenumber domain. Figure 7 is one of the typical results from dynamic analysis (Paper C). In this figure, the horizontal stress distribution on the surface of the pavement along a line under the moving path for different frequencies is depicted. The pavement response is obtained by calculating the transfer function for a typical pavement structure (as shown in Figure 3) and applying equation (6). More details on the pavement response function are given in Paper C. One may notice that the range of wavenumbers in the pavement response increases by increasing the frequency. Moreover, the majority of the wavenumber range for profile 2, which was the rougher pavement, has higher maximum values than the ones for profile 1.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
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<tbody>
<tr>
<td>Ms</td>
<td>4450</td>
<td>kg</td>
</tr>
<tr>
<td>Mt</td>
<td>550</td>
<td>kg</td>
</tr>
<tr>
<td>Cs</td>
<td>15</td>
<td>kN/m</td>
</tr>
<tr>
<td>Ct</td>
<td>2</td>
<td>kN/m</td>
</tr>
<tr>
<td>Ks</td>
<td>1</td>
<td>MN/m</td>
</tr>
<tr>
<td>Kt</td>
<td>1.75</td>
<td>MN/m</td>
</tr>
</tbody>
</table>
Numerical examples and results

Figure 6: Dynamic loads induced on the pavement by a quarter car vehicle model for two different longitudinal road profiles.

Figure 7: Horizontal stress on the surface of the pavement.
Chapter 3.

Pavement surface deterioration

Road surface roughness is one of the most important measures of pavement performance as it affects the ride quality, safety, and vehicle operation cost to a great extent (FHWA, 1998). The main causes of surface deterioration according to Kropáč, and Múčka (2011) are listed as:

a) Surface changes caused by seasonal effects. This is critical for the roads in cold regions where freeze and thaw cycle occurs.

b) Longitudinal profile variation as a result of traffic. This effect is assumed to be a long term effect and rather slow. Particularly, after passing the critical value required for pavement performance, a general maintenance of the pavement is usually required.

c) Presence of local obstacles such as potholes, cracks, ruts. The effects of local obstacles on profile indicators are thoroughly discussed by Múčka (2012).

The deterioration of the pavement surface results in rougher surface and thus higher induced dynamic loads on the pavement. Therefore, an understanding of the mechanism of surface deterioration is necessary in order to better predict pavement service life.

3.1. Longitudinal road profiles

The Swedish Transport Administration (STA) performs measurements on longitudinal profile of the entire road network on a yearly basis. The annual measurements have been carried out since 1987 and road profiles
have been stored since 2001 (Andrén, 2006). The road surface unevenness is measured by a moving vehicle with constant speed and the data is collected at every 10 centimetres.

International roughness index (IRI) is a parameter that has been used to evaluate the smoothness of the road surface. The IRI is an indirect statistical measure of surface roughness that was proposed by the World bank in 1982 and for practical reasons has been used extensively by the pavement community (Karamihás et al., 1999). The IRI is calculated as the ratio of the accumulated suspension deflection of a specific quarter car (i.e. the Golden Car (Gillespie et al., 1980; Sayers, 1995)) by the distance travelled. The IRI was originally developed as a scale for calibrating response-type road roughness measuring systems (Gillespie et al., 1980) and it was the first widely used profile index that was intended to work with different types of profiles.

However, IRI as a single number indicator cannot represent the statistical properties of the pavement surface fully. Several limitations of IRI has been discussed by e.g. Kropáč and Múčka (2005;2009), Delanne and Pereira (2007) and Múčka and Granlund (2012).

Some examples of the limitations of IRI as discussed in the literature can be listed as follows:

a) Roads with the same IRI value may be quite different in their subjectively judged visual features as well as physical and analytical based unevenness indicators (i.e. PSDs and correlation functions (CFs)).

b) The dynamic loads induced at different profiles with identical IRI can be quite different.

c) Roads with irregular forms of unevenness cannot be identified with IRI.

d) IRI does not capture megatexture (5-50 cm) which affects the ride quality.

When it comes to coupling the pavement model with the vehicle model, a more extensive definition of the surface roughness is needed. Power spectral density (PSD) as a direct statistical measure of the road
surface roughness is a more suitable parameter to be used in vehicle-road interaction. The approximation of PSD is usually available with a few parameters.

In this thesis, in order to obtain the PSD of the sections of longitudinal road profiles, the measured data is first filtered for the wavelengths over 50 meters with high pass Butterworth filter. The reason for filtering is that wavelengths longer than 50 meters have no influence on the vehicle response (see Figure 6). The filtering is performed as zero-phase digital filtering so the start and ending transient effects are minimised. The yearly PSD for each section is then obtained using Welch approximation with a Hanning window. The number of overlaps in Welch approximation is 50% of the length of the data for each road section. All the computation is performed in MATLAB® (cf. Paper D).

### 3.2. Prognostic model

In this thesis, the surface deterioration of flexible pavements is investigated based on field measurements. In the interest of obtaining the general trend of pavement surface deterioration, the displacement PSD of longitudinal profile unevenness of 35 road sections with a total length of approximately 60 km has been analysed (see Figure 8). The details about the length of the sections and their locations are given in the appendix of Paper D.

![Figure 8: Map of the location of the analysed road sections in Sweden](image)
In order to calculate the average deterioration function for the selected road sections, the yearly gradient for all 35 road sections along the right and the left track is calculated and then is averaged over the measurement years. In Figure 9 the average gradient of the displacement PSD of 35 road sections, normalized by their amplitudes, is plotted as a function of wavenumber and wavelength.

Based on observation, a general linear deterioration trend has been assumed for the prognostic model. Equation (11) is therefore proposed as a prognostic model for pavement surface deterioration as function of wavenumber, $k_x$ and long-term time (i.e. years), $t_l$:

$$S_x(k_x, t_l) = A(k_x) \cdot t_l + S_{x0}(k_x), \quad (11)$$

Where $A(k_x)$ is the observed evolution function as shown in Figure 9 and $S_{x0}(k_x)$ is the initial displacement PSD (i.e. at $t_l = 0$).

Figure 9: Mean gradient value normalized by the amplitude of the gradient excluding the years with maintenance
3.3. Numerical analysis

The prognostic model shown in equation (11) is used to simulate a case of the evolution of pavement surface roughness and consequently its effect on dynamic loads exerted on the pavement and pavement response. In Paper D more details on longitudinal profile deterioration simulation and relevant results are shown.

In Figure 10 the displacement PSD for a selected road section (Section 5 in appendix of Paper D) is depicted. In the figure, it is shown how the prognostic function, presented in the previous section has been used in order to simulate the longitudinal profile of this section after 10 years, and then is compared with the measured profile.

![Figure 10: Displacement PSD of the longitudinal profile for an example road section, comparison between the initial PSD and measured and simulated PSD after 10 years.](image)

Figure 11 shows the PSD of the dynamic loads from the response of a quarter car to each displacement PSD shown in Figure 10. The quarter car is assumed to move with a constant speed of 20 m/s. The parameters used for the quarter car model is reported in Paper D. The Dynamic Load Coefficient (DLC) is used in order to compare the results of the simulation with measured longitudinal profiles. The DLC is calculated as
the ratio of the RMS of the vehicle dynamic loads to its static load. In Figure 11 the parameters are defined as follows:

- **DLC₀** : The initial DLC, (i.e. at year 2001)
- **DLC₁** : The DLC at the anticipated year (i.e. year 2010) for the measure profile
- **DLC₂** : The DLC at the anticipated year (i.e. year 2010) for the simulated profile

It can be observed in Figure 11 that surface deterioration for this specific road section results in 6% increase in DLC after 10 years. Moreover, simulating the surface roughness deterioration using Equation (11) successfully captures the increase in the magnitude of the dynamic loads on the pavement.

![Figure 11: PSD of dynamic loads from the quarter car, comparison between measure and simulated longitudinal profile](image)

Based on the stochastic dynamic approach in Chapter 2, the framework may be employed for obtaining the non-stationary response of the flexible pavement when the surface deterioration is taken into account. In Figure 12 the response of the pavement as horizontal stress at the bottom of asphalt layer for pavement section 5 is shown. Equation (11) has been used for obtaining the response for two different cases of \( t = 0 \) and \( t = 11 \) years. The details regarding the pavement and vehicle response function are described in details in Paper D. In Figure 12 the
RMS value is calculated as an average measure for the two cases. The differences between RMS values for these four selected frequencies are approximately 100% indicating that the surface deterioration after 11 years increases the dynamic component of stresses in the pavement to double of its value.

Figure 12: Horizontal stress at the bottom of AC layer at frequency of (a) 4e-3 Hz; (b) 1 Hz; (c) 4.9 Hz; (d) 15.1 Hz
Chapter 4.

The effect of dynamic loads on pavement service life

Pavement surface deteriorates during its service life due to various reasons. Some causes of pavement surface deterioration have been explained in the previous chapter. A deteriorated pavement surface is rougher in comparison with a newly built surface, thus it results in higher magnitude of dynamic loads induced on the pavement. Therefore, the magnitude of the traffic load increases during pavement service life and results in accelerated damage (i.e. crack propagation and rutting) in the pavement and consequently higher cost of the project in a life cycle perspective.

4.1. Surface deterioration model

In this section the prognostic model in Chapter 3 has been used in order to simulate the evolution of the exerted dynamic loads on the pavement. In Figure 12 the evolution of the DLC for a quarter car model with the parameters given in Paper E and an average Swedish road is simulated for different values of constant moving speed. The linear evolution of DLC is the result of the linear model for pavement surface deterioration. It can be observed in Figure 12 that by increasing the speed, the initial DLC as well as rate of change of DLC increases. The initial DLC for this case changes between 10 to 30% and the yearly rate of change is between 0.3% to 0.8%, for different speeds.
4.2. Mechanistic empirical design procedure

In order to calculate the pavement service life, PMS Objekt (STA, 2013) as a Mechanistic Empirical (ME) design procedure calibrated for Swedish conditions has been used in this thesis. In the design procedure, two main modes of failure, i.e. fatigue cracking and subbase rutting, are considered. The Swedish transport administration suggests the fatigue failure criterion as follows (STA, 2011):

\[
N_{\text{till},bb} \geq N_{\text{ev}}
\]

\[
N_{\text{till},bb} = \frac{365}{\sum_{i=1}^{m} \frac{n_i}{N_{bb,i}}}
\]

\[
N_{bb,i} = f_s \cdot 2.37 \cdot 10^{-12} \cdot 1.16^{(1.8T_i + 32)} \cdot \varepsilon_{bb,i}^4
\]

where:

- \(N_{\text{ev}}\) Equivalent number of standard axles
- \(N_{bb,i}\) Number of allowed standard axles during climate period \(i\)
- \(\varepsilon_{bb,i}\) Horizontal tensile strain at the bottom of AC layer for climate period \(i\)
In a similar approach, the vertical compressive strain on top of the subgrade is used for calculating the number of allowed axle loadings before rutting failure.

In Figure 14 the schematic method for calculating the reduction in the service life of the pavement when the dynamic loads are included, has been shown. The dynamic loads have been added to the static standard axle loads, assuming a linear evolution of DLC (see Figure 13) over the pavement service life. Maximum horizontal tensile strain at the bottom of AC layer as well as maximum compressive vertical strain at top of the subgrade is calculated for each pavement section and climate period using multilayer elastic theory. Afterwards by applying equation (12) the yearly maximum allowed standard single axles can be calculated.

\[ n_i \] Length of climate period \( i \)

\[ T \] Pavement temperature in °C for climate period \( i \)

\[ f_s \] Correction factor for cracked pavement; \( f_s = 1.0 \) for new constructions

---

**Figure 14:** Schematic method for calculating the reduction in predicted pavement life when the dynamic loads are included
4.3. Life cycle cost analysis

Life Cycle Cost Analysis (LCC) is a methodology for systematic economic evaluation of a project for its defined lifetime (ISO, 2008). An LCC framework developed by Mirzadeh et al. (2013) has been used in this study in order to quantify the impacts of increased dynamic loads on the project cost. The focus in this study is to evaluate the benefits of preventive maintenance activities for e.g. constructing a thin asphalt layer overlay regarding lowering the dynamic impacts from the vehicles and thus increasing the pavement life.

4.4. Case study results

An example of a medium traffic road section is given in this section in order to demonstrate the effects of dynamic loads from the vehicle on the pavement service life and to evaluate the benefits of preventive maintenance The pavement structure designed for this example is shown in Table 3 using PMS Objekt 5.0 (STA, 2013). The road is assumed to have and average annual daily traffic (AADT) of 7800 with 10% heavy vehicles and yearly traffic growth of 1% per year.

The application of a preventive maintenance was studied in order to indicate if it can lower the project LCC by increasing the pavement life span. The preventive maintenance activity consisted of 10 mm milling of the existing pavement and applying a 20 mm overlay (ABT 11). The required thickness of the binder course is obtained by the ME model for a design period of 25 years. The details on mixture properties can be found in a relevant report by Swedish transport administration (STA, 2011).

Maximum horizontal tensile strain at the bottom of AC layer as well as maximum compressive vertical strain at the top of the subgrade is calculated for each pavement section and climate period using multilayer elastic theory. Afterwards, by applying Equation (12), the yearly maximum allowed standard single axles are calculated for each case scenario.
Table 3: Pavement structure configuration of road sections

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bituminous surface layer</td>
<td>50</td>
</tr>
<tr>
<td>Bituminous bearing layer</td>
<td>115</td>
</tr>
<tr>
<td>Unbound base</td>
<td>80</td>
</tr>
<tr>
<td>Crushed rock subbase</td>
<td>200</td>
</tr>
<tr>
<td>Rock bedding</td>
<td></td>
</tr>
</tbody>
</table>

The total energy and time variables were calculated for a functional unit that was defined as construction and rehabilitation of 1 km asphalt pavement per lane for the 25 years design life. Calculations of energy related costs were done based on the price of energy sources as 0.01 (€/MJ) for crude oil, 0.038 (€/MJ) for diesel, 0.024 (€/MJ) regarding electricity price for industries and 0.015 (€/MJ) for residual oil as of 2012. The information regarding transportation distances, the value of time for labour/equipment and the amount of time and energy spent for construction and rehabilitation can be found in Mirzadeh et al. (2013).

![Figure 15: Service life reduction as results of applying the additional dynamic loads for different cases](image)

Implementation of preventive maintenance by reducing the surface roughness can moderate the negative impact of dynamic loads induced from road-vehicle interactions. Furthermore, reduction in the surface roughness can also decrease vehicles fuel consumption. Therefore, application of the preventive maintenance by increasing the pavement life and decreasing the portion of energy related costs can lower the amount of financial risk regarding the cost asphalt pavements (Figure 16). The
application of a 20 mm thin asphalt layer had a lower amount of energy related costs compared to a more traditional thicker rehabilitation. Therefore, by applying the thin asphalt layer the portion of energy related costs dropped by 6-7% for this example.

Figure 16: The amount of energy savings for different DLC rate of change
Chapter 5.
Conclusions and Recommendations

The response of the flexible pavement to moving loads has been investigated in this thesis. The focus has been mainly on the response field of the flexible pavement. Different components of the system such as vehicle and pavement surface roughness models have also been discussed.

5.1. Summary of findings

The focus in this study has been mainly on the effect of vehicular loads on the response of flexible pavement. Therefore in the first step a three-dimensional flexible pavement model with the viscoelastic material properties assigned to the asphalt layer has been developed using FEM. Afterwards two computational frameworks for analysing flexible pavements under moving loads are presented. First a quasi-static computational procedure is performed. A superposition procedure based on the Fast Fourier transform techniques is applied to find the pavement response to an arbitrary loading history. In the second approach, a numerical framework for quantifying the dynamic response of viscoelastic flexible pavements to moving loads has been developed. The dynamic nature of the vehicle pavement interaction problem is taken into account by bringing the road profile roughness into calculations. In order to obtain the response of the pavement to the moving load, first the transfer function for the pavement structure using three-dimensional FEM is calculated. Afterwards, the response is found in frequency-wavenumber domain by multiplying dynamic load and the transfer function.
In the next step, the pavement surface deterioration is investigated based on field measurements of longitudinal road profiles in Sweden. Based on the average gradient of yearly measurements of the road surface roughness in Sweden, a prognostic function is proposed. Furthermore, employing the prognostic function and the previously developed dynamic procedure, it was possible to obtain the yearly response of flexible pavement to dynamic loads based on a non-stationary stochastic procedure. Furthermore, the effect of surface deterioration has been incorporated in ME design framework to investigate the impacts of changes in dynamic loads on pavement service life and LCC of the project.

The computational frameworks presented for calculating the response of the pavement to moving loads are numerically efficient as they utilise Fast Fourier transform technique and the finite element solution is needed to be calculated only once. Such an approach is much more computationally favourable as compared to traditional full scale finite element solution.

Based on quasi-static analysis, it has been found that traffic characteristics have a profound impact on viscoelastic stress redistribution in the pavement structure. Furthermore, a build-up of the tensile stress at the surface of the asphalt layer has been observed, which provides at least a qualitative explanation of the top-down crack initiation found in the field.

Based on the results from dynamic analysis, it was found that as the frequency increases, a higher range of wavenumbers gets involved in the pavement response. For the specific case of horizontal stress at the surface and the bottom of the asphalt layer, the response of the pavement to the rougher profile is approximately 50% higher in the majority of the frequency ranges. The results, based on dynamic analysis show the importance of the dynamic vehicle-road interaction in stress analysis of flexible pavements; as these effects can have considerable influence on the expected pavement service life.

Using a non-stationary stochastic solution, the yearly response of the pavement to moving dynamic loads was obtained. Furthermore the effect of surface deterioration on dynamic component of the stress and strain on the pavement was investigated. Based on the results of a case study, an increase of 100% in the RMS value for the dynamic components of the stress state induced in pavements due to pavement surface profile deterioration after 11 years of pavement service life was observed.
Furthermore, when the effect of surface deterioration was included in an ME design framework, it was observed that the predicted life length of asphalt pavement became shorter. Moreover the application of preventive maintenance was shown to be an economical solution when the rate of change of DLC was high.

5.2. Recommendations for future studies

The effect of tyre contact stresses is a very important aspect of pavement-vehicle interaction. This effect is typically represented with non-uniform normal stresses as well as the presence of tangential stresses that are transferred from the tyre to the pavement. Several studies (e.g., Al-Qadi et al., 2005; Drakos et al., 2001) have shown that accounting for non-uniform tyre contact pressures results in more realistic pavement response. In the current study the analysis has been performed with uniform and normal contact pressure. However, the developed procedure is based on a 3D solution and is thus capable of dealing with non-uniform normal and shear tractions. A detailed study on dynamic effects when more realistic tyre contact pressure is taken into account is recommended for future studies.

Moreover, although the current models presented in this thesis have the sufficient frequency content for predicting the dynamic loads on the pavement (e.g., Cole and Cebon, 1989; Hardy and Cebon, 1994), but some important aspects of the vehicle behaviour, e.g. pitching and bouncing are missing in the model. Perhaps performing the same analysis with a more articulated vehicle model can be beneficial for future studies.

The ME framework has been used in the current thesis in order to investigate the effect of surface deterioration on pavement service life. However due to certain level of empiricism in the design framework these impacts need to be further studied.
Chapter 6.

Summary of appended papers


A general quasi-static computational procedure is established to evaluate stresses and strains induced in the viscoelastic flexible pavement by moving traffic. The procedure is based on superposition principle and is computationally favourable, as it requires only reduced incremental problem to be solved numerically. The impact of traffic speed and density on the mechanical response of flexible pavement is examined numerically. Results relevant for two major modes of pavement’s distress, i.e. cracking and rutting, are reported. It is shown that the state-of-practice layered elastic analysis used in pavement design is unable to capture several important qualitative and quantitative aspects of pavements response.

Paper B: Impact of Long and Heavy Vehicles on Pavement Damage

In this paper the effect of vehicle configuration and traffic characteristics on the damage induced in pavements by traffic is investigated numerically. A three dimensional time-dependent pavement-vehicle interaction analysis is performed in order to study the impact of the parameters mentioned above on the mechanical response of flexible pavements. The analysis is based on a fast and robust computational procedure, developed by the authors. The numerical algorithm utilizes the three-dimensional finite element solution of the reduced problem of one tyre pavement interface loaded with tyre pressure. Afterwards, a superposition procedure based on fast Fourier transform techniques is applied to find the pavement response to moving loads. The method is general and capable of capturing the stress-strain response to any
arbitrary loading history. One particular area of study with employing the current procedure is the analysis of long and heavy vehicle impact on pavement damage. Two major modes of distress, i.e. cracking and rutting have been discussed for different studied cases. It is shown that an accurate numerical model provides a more accurate explanation of different distress modes. Moreover the conventional analysis and design methods with layered linear elastic behaviour assumption for asphalt layer are unable to capture several important aspects of pavement response.

**Paper C: Dynamic Response of Flexible Pavements at Vehicle-Road Interaction**

In this paper a robust and general computational framework that captures the dynamic response of flexible pavements to a moving vehicle is presented. A finite element method is relied upon in order to establish the response function for a linear viscoelastic pavement structure with dynamic effects taken into account. In order to characterise the dynamic loads induced on the pavement by moving traffic, a quarter car model combined with measured road profiles is used. Once both the traffic loads and pavement response functions are known, the stresses and strains induced in the pavement can be obtained in frequency-wavenumber domain through the convolution procedure. The computational procedure developed is applied in the present study to evaluate the effect of the pavement surface roughness on the pavement structure response to truck traffic loading. Stress field parameters governing fracture initiation in asphalt layers are reported for two measured road roughness profiles. It is shown that the dynamic effects at vehicle-road interaction may have a profound influence on the stresses induced in flexible pavements; therefore these effects need to be taken into account for accurate estimation of the road resistance to cracking.

**Paper D: The Non-Stationary Response of Flexible Pavements to Moving Loads**

In this paper the pavement surface deterioration is investigated based on field measurements of surface roughness profiles obtained in Sweden. A predictive function for surface deterioration, based on average gradient of yearly measurements of the road surface profile in Swedish road network, is proposed. In order to characterise the dynamic loads induced on the
pavement by moving traffic a quarter car model is used. Afterwards a non-stationary stochastic approach is used to obtain the yearly response of the pavement to moving loads. The solution is in frequency-wavenumber domain and is given for a non-stationary random case as the pavement surface deteriorates in pavement service life influencing thus the magnitude of the dynamic loads induced by the vehicles. The effect of pavement surface evolution on the stress state induced in the pavement by moving traffic is examined for a specific case of quarter car model and pavement structure. The results showed approximately a 100% increase in the dynamic component of stresses induced in the pavement.

**Paper E: A Life Cycle Cost Approach on Minimization of Roughness-Related Damages on Flexible Pavements**

Due to the surface deterioration the impact form dynamic loads increases gradually during the life span of flexible pavements. A surface deterioration model, based on yearly measurements performed in Swedish road network, has been utilised. The results are discussed for three different case studies with different traffic regimes. It was indicated that the predicted pavement service life decreased considerably when the extra dynamic loads, as a result of pavement surface deterioration, has been taken into account. Furthermore, the effect of performing a preventive maintenance (i.e. thin asphalt layer) has been studied based on an LCC framework. The application of the preventive maintenance was shown to be effective, especially for high deterioration rates.
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