The effect of road surface deterioration on pavement service life



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Abstract

The effect of pavement surface deterioration on pavement service life has been studied for a set of case studies. The Swedish mechanistic empirical design method is used in order to analyse the pavement performance under dynamic moving loads while the longitudinal profile unevenness is updated on yearly basis. The surface evolution assumed in the case scenarios are chosen in relevance with the general trend of surface deterioration in Swedish road network. Results from the case studies indicate that the pavement service life is highly affected by pavement surface deterioration, especially for pavement segments with high traffic. Moreover predictive maintenance for high traffic road segments might be beneficial as it increases pavement service life and decreases the user related costs, e.g. vehicle fuel consumption.

Keywords: *Dynamic axle loads; Road roughness; Flexible pavement; Stochastic analysis, Pavement surface deterioration*

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1 Introduction

The effect of dynamic loads exerted on the pavement has often been neglected in pavement design procedures. Traffic loading is considered to be one of the main causes of pavement failure in most of the cases, therefore underestimating the magnitude of the load applied on the pavement can result in overestimating the pavement service life. The issue becomes even more significant with introduction of heavier and longer trucks into the road network.

Dynamic loads are generated as a result of the interaction between vehicle suspension system and pavement surface roughness. Dynamic loads are assumed to increase pavement damage approximately by 20 to 30%.(Cebon, 1988). 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. The effect of surface roughness is initially small and increases in time as the surface becomes rougher and consequently the development of different crack types on the road surface accelerates considerably. The heavy traffic and environmental effects causes the surface to deteriorate, changing its statistical characteristics in time which result in a non-stationary surface irregularity description. Therefore the response of the pavement is not constant during its service life but is changing as the surface deteriorates in time.

In the current paper, three different case scenarios where road segments with different traffic regime are analysed when the extra dynamic loads from vehicle-pavement interaction as well as the pavement surface deterioration has taken into account. The results indicate the great impact of pavement surface deterioration and vehicular dynamic loads on pavement service life.

2 Surface deterioration model

Road surface unevenness 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 pavement surface roughness changes during its service life due to various reasons resulting in a rougher surface and eventually higher amplitude of exerted dynamic loads from the vehicles to the pavement. The main causes of surface deterioration according to Kropáč, and Múčka (2008) is listed as:

1) Surface changes caused by seasonal effects,

2) Longitudinal profile variation as a result of traffic loading,

3) Presence of local obstacles such as potholes, cracks, ruts.

In a study by Khavassefat et al. (2014) the general surface roughness evolution trend in Sweden is studied in detail. In the interest of obtaining the general trend of pavement surface deterioration, the displacement Power Spectral Density (PSD) of longitudinal profile unevenness of 35 road sections with a total length of approximately 60 km has been analysed. The location of the sections is shown in Figure 1. The analysed road sections are measured by the Swedish road administration (SRA) on yearly basis. The collected data is during 11 years from 2001-2011. The road surface unevenness is measured by a moving vehicle with constant speed and the data is collected at every 10 centimetres.

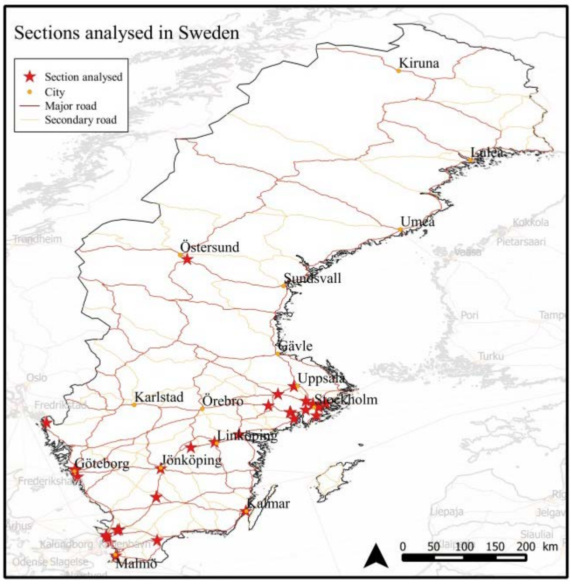


Figure 1 : Geographical location of the analysed road sections

The evolution of displacement PSD for each road section is studied by obtaining the yearly gradient of displacement PSD and averaging the gradient for all of the selected road sections. In Figure 2 the average gradient of the displacement PSD of 35 Swedish road sections, normalized by their amplitudes, is shown as a function of wavenumber and wavelength. In principal the deterioration related to the surface occurs in the short wavelength band while the deterioration in long wavelength band is linked to the whole structure of the pavement (Kropáč and Múčka, 2008). The general trend in Figure 2 is shown with a red line. One may see in Figure 2 that the deterioration rate is higher for the shorter wavelength range in comparison with the longer wavelengths.

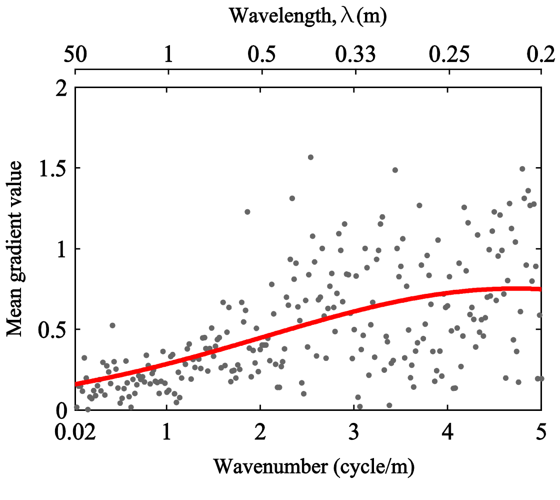


Figure 2 : Mean gradient value normalized by the amplitude

A general linear trend for evolution of displacement PSD was observed for the analysed data. Based on physical deterioration models, it is a viable argument that an exponential model may be a better physical representative of deterioration process. However, as a consequence of frequent maintenance of the road network, there is no data backing up this hypothesis therefore a linear model based on pure observation is considered in this study.

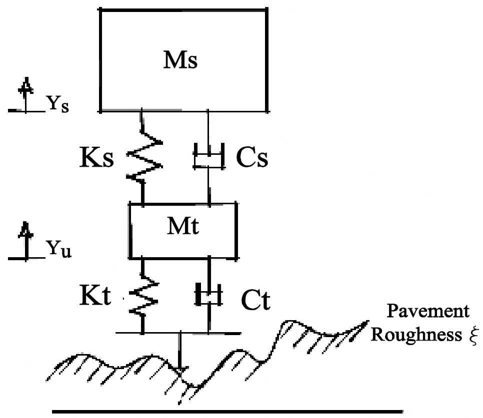
Base on the linear evolution hypothesis the equation below is proposed as a prognostic model for pavement surface deterioration as function of wavenumber, k_x and long-term time (i.e. years), t_l :

$$S_\xi(k_x, t_l) = A(k_x) \cdot t_l + S_{\xi_0}(k_x), \tag{1}$$

where $A(k_x)$ is the observed evolution function as shown in Figure 2 and $S_{\xi_0}(k_x)$ is the initial displacement PSD (i.e. at $t_l = 0$).

Dynamic loads as a result of interaction of vehicle suspension system and pavement surface unevenness are exerted to the pavement structure. In this study a quarter-car model has been used in order to quantify the dynamic loads on the pavement. The schematic view of the vehicle model and the parameters are shown in Figure 3.

In Figure 4 the evolution of Dynamic Load Coefficient (DLC) for 50 years for an average road section in Sweden, using equation (1) and the vehicle parameters given in Figure 3, is shown. The DLC is calculated as the ratio of root mean square value of the dynamic loads to the vehicle static load.



Symbol	Value	Unit
Ms	8900	kg
Mt	1100	kg
Cs	40	kNs/m
Ct	4	kNs/m
Ks	2	MN/m
Kt	3.5	MN/m

Figure 3 : Quarter car model with 2 degrees of freedom (Quarter car data from (Cebon, 2000))

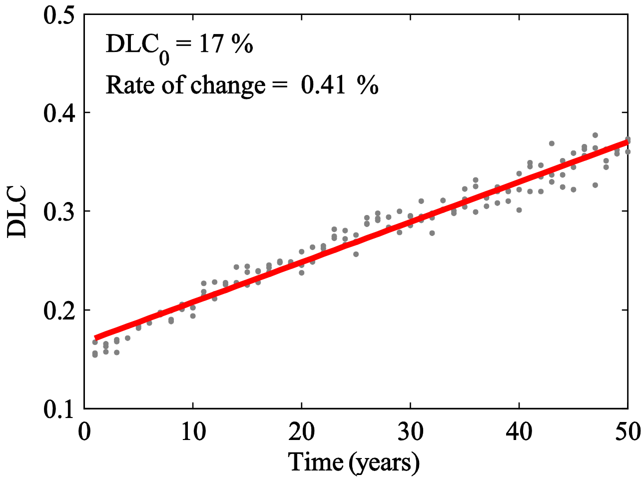


Figure 4 : Evolution of DLC as a result of surface deterioration (The general trend of an average road in Swedish road network)

3 Case study

Three different road sections with different traffic and rehabilitation conditions are analysed in this section in order to study how the surface deterioration and rehabilitation activities affect the pavement service life. The case scenarios to be examined are listed as below:

A) A highway with moderate-low traffic, which is not maintained in the last 20 previous years.

B) A highway close to the capital, with heavy traffic which is not maintained in last 20 previous years.

C) A highway with high traffic flow and frequently maintained over last 20 previous years.

The pavement structure is designed for the three aforementioned case scenarios using PMS Objekt which is a Mechanistic Empirical (ME) design method used in Sweden. In the design procedure, two main modes of failure, i.e. fatigue cracking and subbase rutting, are considered. In addition to the previously mentioned distress modes, PMS Objekt can estimate the damage due to frost heave. In the model the horizontal tensile strain at the bottom of asphalt layer is used, in order to estimate the number of allowed axle loadings before fatigue cracking failure occurs. 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. The Swedish transport administration suggests the fatigue failure criterion as follows (Trafikverket, 2011a):

$$N_{till,bb} \geq N_{ekv}$$
$$N_{till.bb} = \frac{365}{\sum_{i=1}^{m} \frac{n_i}{N_{bb,i}}}, \qquad (2)$$
$$N_{bb,i} = f_s \frac{2.37 \cdot 10^{-12} \cdot 1.16^{(1.8T_i + 32)}}{\varepsilon^4_{bb,i}}$$

where:

N_{ekv}	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
n_i	Length of climate period i
T	Pavement temperature in ºC for climate period i
f_s	Correction factor for cracked pavement; $f_s = 1.0$ for new constructions

Fatigue cracking is mainly the critical failure mode according to PMS Objekt. However it should be pointed out that top-down cracking (i.e. cracks that initiates on the surface of the pavement and propagate downwards) is more common in Europe in comparison with fatigue cracking and rutting (COST 333, 1999). However as PMS Objekt is calibrated with field measurements in Sweden without considering the cause of crack development, top-down cracking is also captured empirically in the model (Gullberg et al., 2012).

The structure for all three cases consists of 50 mm wearing course above a layer of binder course and a 500 mm granular unbound foundation layer. The wearing course is Dense Asphalt Concrete (ABT 11), a dense graded asphalt mixture with maximum aggregate size of 11 mm, and the binder course is Gravel Asphalt (AG 22), which is an asphalt bound foundation layer with maximum aggregate size of 22 mm (Gullberg et al., 2012). The required thickness of the binder course is obtained by the ME model for a design period of 20 years. It has to be pointed out that for calculating the required thickness of the binder course layer, PMS Objekt removes 20 mm from the wearing course during the design procedure. The details on mixture properties can be found in a relevant report by Swedish transport administration (Trafikverket, 2011b).

Initially the binder thickness for the pavement structure is designed without taking into account the added dynamic impact and surface evolution during the design life. The ESALs and the required binder thickness (i.e. the wearing course and the binder course) for each case scenario are listed in Table 1.

Table 1 : Details of the case scenarios

Scenario	ESALs (Millions)	Total thickness of binder layer (mm)	% DLC_0	% Rate of change	Designed Life	Service Life
A	8	160	10	0.40	20	17
B	15	180	10	0.80	20	15
C	15	180	10	0.80	20	19

Afterwards, for each case scenario, the service life is calculated considering the additional dynamic loads exerted on the pavement. The initial dynamic coefficient and the rate of change are assumed separately for each case scenario based on their traffic regime and general trend of surface deterioration in Sweden (Figure 4). The assumption here is that most of longitudinal variation is according to traffic loading.

An initial dynamic coefficient (DLC_0) of 10% is chosen for all of the three cases. The value is considered to be lower than the average DLC_0 (as shown in Figure 4) as the quality of the pavement surface is usually better right after construction. The value is chosen in accordance with the DLC of a "good road" in interaction with the quarter car model with the parameters shown in Figure 3 (Cebon, 2000; ISO, 1996). The rate of change for case A, is assumed to be following the general trend in Sweden thus a yearly increase of 0.40% is considered. For case B, as a result of higher traffic flow, the rate of change is assumed to be 100% higher than the general trend thus the yearly increase is assumed to be 0.80%. Finally for case C the same trend is chosen as case B but after 12 years this section of highway has been resurfaced therefore the surface roughness has been improved.

One may see in Figure 5 that in the extreme case scenario (case B) with high traffic regime and no rehabilitation, the pavement service life is reduced to 15 years. For case A the service life is reduced to 18 years. Finally the performance of rehabilitation in case C has been proven to be useful and therefore only one year life reduction has been observed.

Rolling resistance is another important matter that is directly affected by change of pavement surface roughness during its service life. Rolling resistance has direct relationship with fuel consumption and greenhouse gas emissions. Wang et al. (2012) have studied the change of surface roughness and rehabilitation process on the two aforementioned parameters, using a LCA (i.e. life cycle assessment) model. In their case study, it is shown that when a life cycle scope is considered, rehabilitating a rough pavement segment with high traffic has a great potential to reduce fuel consumption and greenhouse gas emissions.

Regarding the results presented in this paper, even if very little service life change has been observed in case A and C, but the increase of fuel consumption and greenhouse gas emissions are still considerable and have to be studied in a life cycle scope together with mechanical failure. A detailed study on cost estimation of pavement surface deterioration will be the subject of future studies.

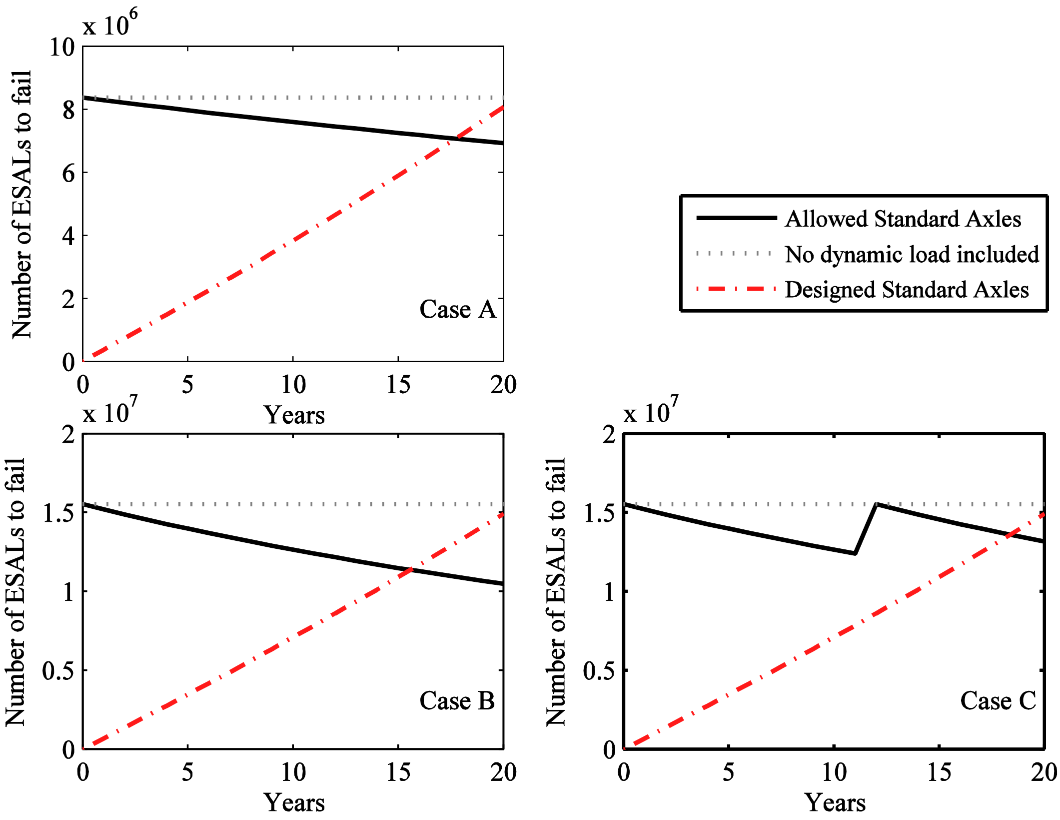


Figure 5 Effect of surface roughness on allowed standard axles during pavement service life

4 Summary and Conclusions

The effect of pavement roughness and its evolution during the pavement service life is studied in this paper. The effect of the surface roughness is initially small but increases during pavement service life resulting in higher dynamic loads and consequently higher damage in pavements. The effect of surface evolution is shown in this paper through analysing three different scenarios. The surface evolution assumed in the case scenarios are chosen in relevance with the general trend of surface deterioration in Swedish road network. The pavement sections, for each case scenarios, are initially designed without taking the dynamics into account and afterwards are analysed when the dynamic loads are applied on the surface as a result of surface roughness interaction with the vehicle suspension system.

The results indicate that for a road segment with high traffic, the surface deterioration has a great influence on the pavement service life. The effect however is less when the traffic volume is lower. Furthermore, based on the results of the case studies a preventive rehabilitation procedure can be effective in order to increase the pavement service life. Considering that a simple milling and resurfacing procedure is not a big investment it might be beneficial for high traffic road segments to perform preventive maintenance of the surface to avoid service life shortening due to increase of dynamic loads on the pavement.

The effect of surface roughness on rolling resistance along with structural failure in the pavement structure must be studied in a life cycle scope. In the future studies, it is intended to study the effect of surface roughness evolution on pavement management and rehabilitation decisions together with a LCC (i.e. life cycle cost) framework.

5 Acknowledgement

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