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Review of longitudinal pavement roughness prediction tools

Abstract. Many road agencies use special tools for managing their assets. Article provides overview of most known pavement management systems. Most of all describing pavement management systems have special tools for prediction longitudinal roughness, rutting, friction, Pavement Condition Index (PCI), Surface Distress Index (SDI), Structural Adequacy Index (SAI) and Ride Comfort Index (RCI) etc. Among the factors of performance deterioration the following external factors are the most frequently singled out: the number of freezing and thawing cycles, temperature, humidity, precipitation, ground water depth level, the number of traffic load repeats in daily average annual traffic intensity or equivalent single axle load (ESAL); internal factors: material type, structural strength and thickness, subgrade material, etc. There is an analysis of current longitudinal roughness prediction models, which are used on the project and network level, in the article. The article contains deterministic models of longitudinal roughness prediction suggested by Russian and foreign authors at different periods of times.

Keywords: pavement management system; prediction models; pavement performance; roughness

To ensure the most efficient asset management the highway agencies of developed countries use pavement management systems at network and project levels [1]. The key element of many of those systems is the capability to predict the occurrence of critical state of pavement performance and/or functional parameters which determine the type and sequence of repair, preventive and other measures taking into account actual financing. The table 1 based on the analyzed literature references [2-11] contains data on the prediction tools of the best known pavement management systems.

Table 1

Prediction models used in various pavement management systems

Expert system	Brief description of applied deterioration models
PMAS	Markov models are used
AgilAssets®Pavement Analyst	Prediction of pavement performance is based on the analysis of performance deterioration curves
PAVEMENTview	Doesn't have individual prediction models. Any models can be used
PERS	Doesn't have individual prediction models
ICON	Doesn't have individual prediction models. Any models can be used
PMSPRO™	Doesn't have individual prediction models
HPMA	Prediction models of PCI or another indices
MicroPAVER	Prediction of pavement performance is based on the analysis of PCI deterioration curves
TAMS	Prediction of pavement performance is based on the analysis the historical data
Vejman.dk	Roughness models are used (IRI)
dROAD/dTIMS	Roughness, rutting and damages models are used
WDM	Prediction of pavement performance is based on the analysis the historical data
Asset Manager NT	Doesn't have own prediction models. Results of any another PMS use for create scenario «what if»
HDM-4	Roughness as result of structural deformation and defect development are used. Rutting and Square of cracking can be used for prediction separately
Stantec PMS/RoadMatrix	Deterioration models Surface Distress Index (SDI), Structural Adequacy Index (SAI) and Ride Comfort Index (RCI)
HIPS	Markov models are used
RoSy® (PMS)	Doesn't have individual prediction models. Prediction models of HDM-4 are used
RONET	Simplify prediction models of HDM-4 are used
RoadMatrix™	Prediction models of Pavement Quality Index (PQI) are used
Norwegian PM System	Roughness and rutting models are used
MEPDG	Prediction models of cracking and rutting are used
FHWA HPMS	Prediction models of Pavement Serviceability Rating (PSR) are used
CCPMS	Doesn't have prediction models
LBPMS	Doesn't have prediction models
RSMS99	Doesn't have prediction models
CTL PMS	Doesn't have prediction models
dROADLOG	Doesn't have prediction models
Dynatest PMS	Doesn't have prediction models
PMSpro 2000	Doesn't have individual prediction models. Any models can be used
Visual/PMS™	Prediction of pavement performance is based on the analysis the historical data
DSS	Prediction models of Pavement Condition Index (PCI) are used
MPMS	Prediction model of Pavement Structural Condition rating (PSC) is used
Swedish PMS	Prediction models of HIPS are used
ELMOD	Roughness, rutting, friction and wearing models are used

In the majority of the above management systems pavement management is carried out relying on performance indices which are the first and foremost to ensure comfortable driving.

Among the factors of performance deterioration the following external factors are the most frequently singled out: the number of freezing and thawing cycles, temperature, humidity, precipitation, ground water depth level, the number of traffic load repeats in daily average annual traffic intensity or equivalent single axle load (ESAL); internal factors: material type, structural strength and thickness, subgrade material, etc.

Many pavement management systems make use mainly of the deterioration-time relation. The typical deterioration curve is shown in fig. 1a. However, the nature of pavement deterioration is not always like this: inverted deterioration curves (fig. 1b) were obtained by Haas [12] during monitoring of the pavements designed for heavier traffic load than the observed one. In this case the crucial influence during the change of performance was exerted primarily by climate and weather.

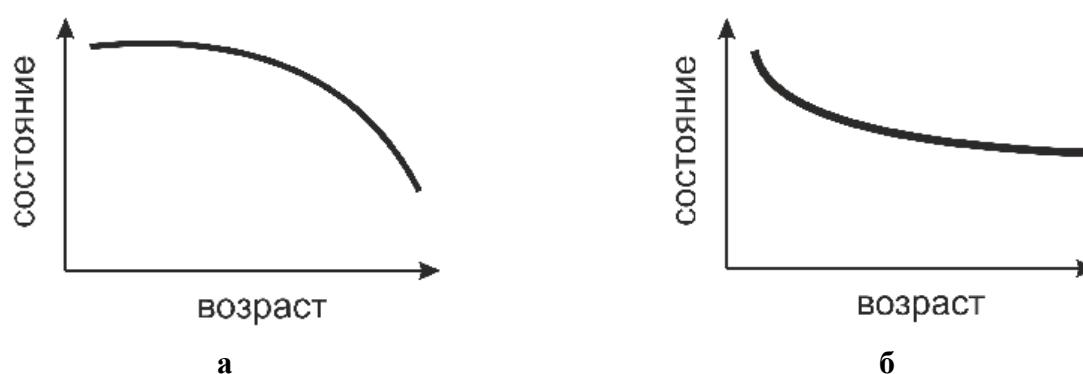


Figure 1. Pavement deterioration curves: *a* - when the traffic load corresponds to the design load, *b* - when the traffic load is lower than the design load

Raymond [13] points to high impact of local factors on performance deterioration. Some international models, including the World Bank's Highway Development and Management Model HDM-4 [14], allow the user to calibrate models according to local specific features.

In general, deterioration models may be divided into deterministic and probabilistic ones.

The deterministic model returns one state value for the predefined input data set [15]. Deterministic models are usually shown as functions. The simplest ones are based on linear regression, however exponential functions and other more complicated ones may return more exact results.

Further, deterministic models are divided into mechanistic (theory-based), empirical (experiment-based), mechanistic-empirical (theory and experiment combined) or those based on expert evidence.

Mechanistic models are based on physical laws. For example, pavement deterioration may need application of relations between stresses, strains, and loads. Typically mechanistic models as is are not applied in pavement management. Moreover, it is believed to be impossible: in [16] it is mentioned that there are no solely mechanistic models for deterioration prediction, in [17] it is stated that mechanistic models are impractical for prediction, although in [18] it is assumed that there are no absolutely mechanistic models, however there are no reasons preventing from their designing. Nevertheless, mechanistic models are not used in prediction of pavement condition due to a great number of aspects.

Empiric models are developed to predict conditions depending on such variables as age, type of material, loading conditions, etc., typically via regression. This type of models is often used when deterioration cannot be explained mechanistically. Schram [19] found out that 91% of Canadian and American agencies used empirical models of performance deterioration. The majority of the countries

of Northern Europe apply empirical linear extrapolation of the current condition of pavement in their management systems too [20].

Many deterioration models (prediction models) fall into the mechanical-empirical category. They include calculation of mechanical reactions (for example, stresses, strains, etc.) and other measured variables for prediction of conditions. This type of models is often applied for performance deterioration modeling [13, 19, 21, 22]. The models yield good results and it is believed that they model deterioration more precisely than empiric models.

The following approaches are used to achieve deterministic models [23]:

- straight (or simple??) linear extrapolation;
- regression analysis (linear, multiple, special);
- polynomial interpolation (least square method);
- exponential analysis.

Linear extrapolation is used for performance prediction when a limited survey data amount is available. It was ascertained [24] that the deterioration curve had not linear, but curvilinear shape; that is why this approach is used for specific road sections only.

Multiple linear regression is one of the simplest forms of the deterministic model and is used when more than one factor influences a dependent variable [15]. The following equation conforms to the model:

$$\hat{y} = b_0 + x_1 b_1 \dots + x_k b_k \quad (1)$$

where $b_0, b_1 \dots b_k$ are regression coefficients, \hat{y} is a predicted value of the dependent variable, $x_1 \dots x_k$ are values of independent variables. Concerning pavement deterioration \hat{y} is a parameter of performance, $x_1 \dots x_k$ are factors influencing the condition (age, materials, location, traffic intensity, etc.). To find coefficients $b_0, b_1 \dots b_k$ the least square method is typically used.

Exponential (S-curve) is usable in predicting of variable changes (for example, that pertinent to driving comfort) as function of the other variable (for example, age of road structure).

In probabilistic models the output parameter is probability that the asset (for example, road structure) is in a specific condition for the suggested input parameter set. There are many different types of models in this group.

One of the most popular probabilistic models used in asset deterioration modeling is Markov chain [15]. Markov models give probability p_{ij} that the element in i condition at t time step will be in j condition at $t + 1$ time step. These transition probabilities are arranged in the transition matrix:

$$P^{t,t+1} = P(X_{t+1} = j | X_t = i) = \begin{bmatrix} p_{11} & \dots & p_{1j} \\ \dots & \ddots & \dots \\ p_{i1} & \dots & p_{ij} \end{bmatrix} \quad (2)$$

where $p_{ij} \geq 0$; $i, j \geq 1$; $\sum_{k=1}^j p_{i,k} = 1$.

Distribution of the asset (road structure) chain conditions at $(t + n)$ time can be found through the product of the current distribution and transition matrixes:

$$Q(t + n) = Q(t) P^{t,t+1} P^{t+1,t+2} \dots P^{t+n-1,t+n} \quad (3)$$

During deterioration modeling p_{ij} is usually defined as probability of deterioration of i condition to j condition.

While in the time homogeneous Markov model the prediction condition depends on the current condition only, in semi-Markov or nonhomogeneous models the independently distributed random values are used for time modeling between states. Thus, the model depends on time. From the point of view of the tangible asset deterioration it means that probability of deterioration to the next condition increases with the asset age. Semi-Markov models require more data for definition of additional parameters and are more complicated in implementation than the time-homogeneous Markov model [25].

The other commonly used probabilistic model is logistic regression. Unlike multiple linear regression where output characteristic is asset condition, logistic regression defines probability of the asset being in a specific condition with the predefined set of independent variables [15]:

$$E(Y = y|X) = P = \frac{1}{1 + e^{-(b_0 + \sum_{i=1}^k b_i x_i)}} \quad (4)$$

The literature shows various models of pavement longitudinal roughness deterioration. They may be classified into four categories: models related to structure effect; models based on temporal effect; models considering correlation between temporal and structure factors; and models where structure, surface and temporal effects define longitudinal roughness.

The table 2 contains deterministic models of longitudinal roughness prediction suggested by Russian and foreign authors at different periods of times.

Table 2

Deterministic prediction models of longitudinal roughness

Reference	Model
[26]	$R_t = R_0 + s(S)N_t$ where: $s(S)$ - function of modified structural number, R_0, R_t - roughness at time 0 and t, respectively, N_t - cumulative number of equivalent 18-kip (80 kN) standard axle loads to time.
[27]	$S_t = S_0 \left[1 + c \cdot E_{min}^d \left(nN_1 \frac{q^t - 1}{q - 1} \right)^{a \cdot E_{min}^b} \right]$ where: S_t и S_0 - roughness at times t and t = 0 respectively by Bump Integrator, cm/km, a, b, c, d - coefficients determined for each data set, n - duration of design period, day/year, N_1 - number of traffic load at first year, q - traffic volume increment in time t, E_{min} - minimum requirement E-modulus, MPa.
[28]	$\Delta R_t = aR_t \Delta t - b$ where: Δt - increment in time, a, b - constant parameters which are environmental parameters of rainfall, elevation, freeze-thaw cycles, temperature, etc., R_t - roughness, in/m.
[29]	$R_t = C_0 + C_1 t$ where: R_t - roughness of homogenous section, in/m, t - year since the treatment, C_0, C_1 - regression coefficients.
[30]	$R_t = R_0 + at^b$ where: t - pavement age, in years, a, b - coefficients determined for each data set.

Reference	Model
[31]	$IRI_d = IRI_i + (IRI_1 + IRI_i) \left(\frac{A_d}{A_1}\right)^{1.5}$ <p>where: IRI_d - predicted roughness at a desired future date, mm/m, IRI_i - roughness just after the latest rehabilitation, mm/m, IRI_1 - latest recorded roughness, mm/m, A_d - age of the pavement surface at the desired future date, years, A_1 - age of the pavement surface when the latest roughness recording was made, years.</p>
[32, 33]	$PSC = C + (mA^P)$ <p>where: A - age of pavement since overlay or construction, years, C - model coefficient (~100), m - slope coefficient, P - constant.</p>
[34]	$IRI = IRI_0 + e^{(a-b \cdot c^x)}$ <p>where: IRI - predicted roughness at a desired future date, m/km, IRI_0 - roughness at time 0, m/km, $x = \ln(t)$, t - age of pavement, years, a, b, c - model coefficients.</p>
[35]	$IRI = 42 + 1,8 \cdot AGE + 0,0004 \cdot AADT$ <p>where: AGE - age of pavement since overlay or construction, years, $AADT$ - average annual daily traffic, veh/day.</p>
[36]	$S_t = \alpha \cdot Q_t + \beta$ <p>where: α - empirical coefficient for particular local conditions, β - roughness at time 0 just after the latest rehabilitation by Bump Integrator, cm/km, Q_t - total load intensity for t period, million gross tonn.</p>
ДМД 02191.5.011- 2011	$IRI_T = IRI_0 + K \frac{\sum_1^T N}{10^6} \cdot \frac{IRI_0}{IRI_H}$ <p>where: IRI_T - predicted roughness at time T, mm/m, IRI_0 - roughness at time 0, mm/m, IRI_H - roughness just after the latest rehabilitation, mm/m, $\sum_1^T N$ - total number of traffic load in estimate period T, number/lane, K - model coefficient.</p>
[23]	$RI_t = [RI_0 + 725(1 + SNC)^{-4.99} NE_{4t}] e^{0.0153t}$ <p>where: RI_t, RI_0 - roughness at times t and $t = 0$ respectively, m/km, NE_{4t} - cumulative equivalent standard axle loadings until time t, million ESA/lane, t - age of pavement since overlay or construction, years, SNC - modified structural number.</p>

Reference	Model
[37]	$\Delta IRI_i = k_r [196.74 \cdot STRUC + 0.016 \cdot \Delta crx + 0.25 \cdot \Delta rut + 0.972 \cdot ENVIR]$ <p>where: k_r - calibration coefficient for roughness, ΔIRI_i - cumulative lane roughness at the year «i» after the initial roughness IRI_0, m/k), Δrut - cumulative lane rut depth at the year «i» after initial densification, mm, Δcrx - cumulative percentage area of cracking after cracking has commenced, % $STRUC$ - cumulative structural condition of the pavement «i» years after construction/rehabilitation under traffic loading, $ENVIR$ - cumulative environmental damage on the pavement «i» years after construction/rehabilitation.</p>
[38, 39]	$dIRI = k_{gp} (a_0 e^{k_{gm} m AGE} (1 + SNC a_1)^{-5} NE_{4t} + a_2 AGE) + k_{gm} m RI_a$ <p>where: k_{gp} - coefficient of degradation rate, a_0, a_1, a_2 - coefficients HDM-4, m - climate factor, AGE - pavement age, years, SNC - modify structural number, NE_{4t} - total ESAL up to time t, million ESA/lane, RI_a - current value of roughness IRI, m/km.</p>
[11]	$IRI_t = IRI_0 + a \left(\frac{N}{10^6} \right)^b$ <p>where: IRI_0, IRI_t - roughness at times t and t = 0 respectively, m/km, N - total number of vehicle during analyzing period, vehicle, a, b - model coefficients.</p>

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Обзор инструментов прогнозирования продольной ровности дорожных покрытий

Аннотация. Многие дорожные агентства для эффективного управления активами пользуются специализированными инструментами. В статье представлен обзор наиболее известных систем управления состоянием дорожных конструкций. Многие из рассмотренных систем управления дорожных конструкций используют инструменты прогнозирования таких показателей как продольная ровность, колейность, коэффициент сцепления, Pavement Conditional Index (PCI), Surface Distress Index (SDI), Structural Adequacy Index (SAI) and Ride Comfort Index (RCI) и др. Агентства используют как простые линейные модели деградации параметров, так и вероятностные подходы (например, модели Маркова). Среди факторов ухудшения эксплуатационного состояния чаще всего выделяют следующие внешние факторы: число циклов замораживания / оттаивания, температура, влажность, осадки, глубина залегания грунтовых вод, число повторений транспортной нагрузки в среднесуточной годовой интенсивности движения или эквивалентной единичной осевой нагрузке (ESAL); внутренние факторы: тип материала, прочность и толщину конструкции, материал земляного полотна и др. Проведен анализ моделей прогнозирования продольной ровности используемых на проектом и сетевом уровнях. Представлены детерминистические модели прогнозирования продольной ровности, предложенные отечественными и зарубежными авторами в разные годы.

Ключевые слова: система управления состоянием дорожных конструкций; модели прогнозирования; эксплуатационное состояние; продольная ровность

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