STRUCTURAL EVALUATION OF FLEXIBLE PAVEMENTS USING NON DESTRUCTIVE TESTS

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ABSTRACT

The aim of this paper is to contribute to the improvement of the methodologies used in structural pavement evaluation, concerning in particular the backcalculation of layer moduli based on Falling Weight Deflectometer (FWD) together with Ground Penetrating Radar (GPR) test results and using Artificial Neural Network (ANN) technique for the analysis. A brief description of the test procedures and analysis methods is made.

The bearing capacity of a pavement is generally evaluated through non-destructive load testing (NDT). Based on the deflections measured in situ and taking into account the pavement layer thickness and material characteristics a response model of the pavement is established. The layer thicknesses are normally obtained through cores and, if available, GPR measurements. The elastic moduli of the layers are adjusted until the deflections calculated are close to the deflections measured during testing (backcalculation).

There are several methods for backcalculation of layer moduli from Falling Weight Deflectometer (FWD) test results. However, the results obtained are not always satisfactory, for several reasons, such as the existence of multiple solutions or errors in the pavement layer thickness.

An application of the proposed method, combining FWD and GPR tests, is presented. The analysis of the results showed the suitability and advantages of the proposed methodology for structural pavement evaluation. From the experience gathered some recommendations for use of ANN in pavement structural evaluation were drawn, in view of obtaining reliable results.

1. INTRODUCTION

Pavement maintenance is becoming an important issue, as the construction of new roads tends to decrease, the aggressiveness of traffic loads is increasing and the functional requirements for the existing roads are becoming more demanding. More efficient methods for pavement monitoring and structural evaluation are required in order to ensure a good serviceability and to provide adequate maintenance solutions for the pavements.

The pavements' structural condition is one of the main factors to be taken into account for pavement maintenance planning. Non-Destructive Testing (NDT) of pavements is increasingly being recognised as an effective way to obtain information about their structural behaviour. In order to evaluate the bearing capacity of a pavement, using a mechanistic approach, a structural model of the pavement is required for the estimation of its residual life. This structural model is obtained through interpretation of non-destructive tests. Using layer thickness data as input, the elasticity moduli (E moduli) of the pavement's layers are "backcalculated" from the deflection basin measured with non-destructive load testing equipment. In this way, the pavement bearing capacity is evaluated, and the remaining pavement life can be estimated, taking into account the future traffic.

The combination of results from FWD and GPR tests can provide a major improvement to the quality of the results. Furthermore, the use of ANN is an interesting option for the backcalculation of layer moduli. This paper presents the main results of a research study where these issues were addressed.

2. IMPROVED METHOD FOR PAVEMENT EVALUATION

2.1. Non Destructive Tests

In the case of an existing pavement, it is essential to evaluate the pavement structural condition in order to set up an adequate pavement response model, since the material properties change in time. Furthermore, the existing information on the initial pavement structure is not necessarily available or accurate.

Falling Weight Deflectometer

The Falling Weight Deflectometer (FWD) is presently the device for deflection testing most widely used in Europe, North America and Japan (Irwin, 2002). The test load is obtained by dropping a weight from a certain height on a set of buffers. The deflections are measured by a set of deflection transducers resting on the surface. This equipment has the advantage that the impact load applied on the pavement can be changed by changing the weight, the height and the loading plate. In this way simulation of various loading is enabled. The equipment measures the pavement response in 6 to 9 points, resulting a deflection bowl that reflects the influence of different layers on pavement response. (see Figure 1). The measurements are performed at equal distances, chosen according to the length of the section to be tested (from 10 to 100 m).

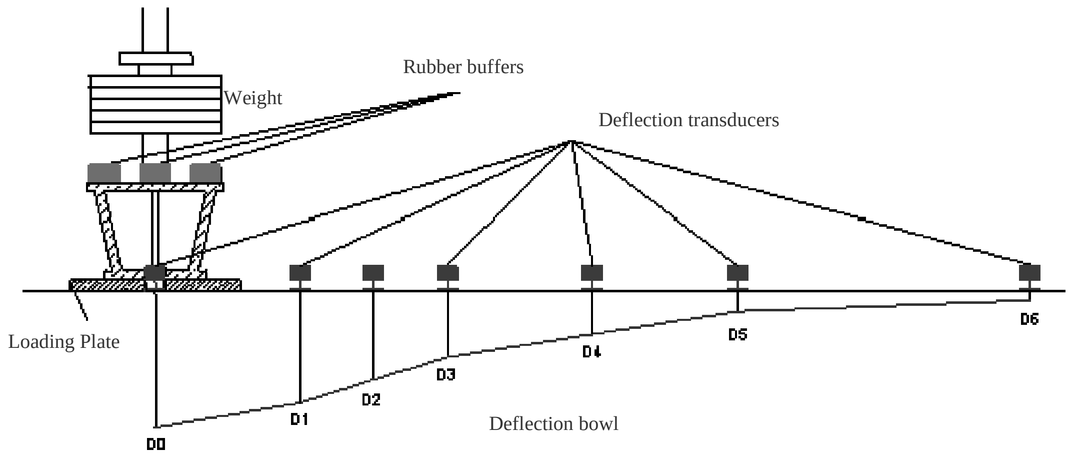

Figure 1. Deflection distribution scheme within the pavement structure under FWD action

The measured deflection bowls, together with the information on layer thickness, are used for the estimation of "in situ" bearing capacity (Antunes, 1993).

Ground Penetrating Radar

In general, information about the existing pavement structure thickness can be obtained from historical data, coring, trial pits and Ground Penetrating Radar (GPR). Normally, the best approach is to gather as much information as possible, from different sources.

Layer thickness may be quite variable along a pavement structure, therefore continuous information on thickness is needed. Accurate measurements are essential for the analysis of FWD tests, particularly for the backcalculation process. A continuous measurement of the layer thicknesses has become possible with the application of GPR for substructure evaluations.

Air-coupled antennas are the most widely used for pavement studies. The antennas are suspended on a van or a trailer and allow for measurements at high speed.

The GPR transmits short duration electromagnetic pulses from a transmit antenna into the material being tested (Figure 2) and picks up the reflected energy in the receive antenna. The reflected wave gives information about the pavement’s structure. The wave amplitude is related with the difference in dielectric properties (ε_i) of two adjacent layers, while the travel time gives the interface location beneath the surface.

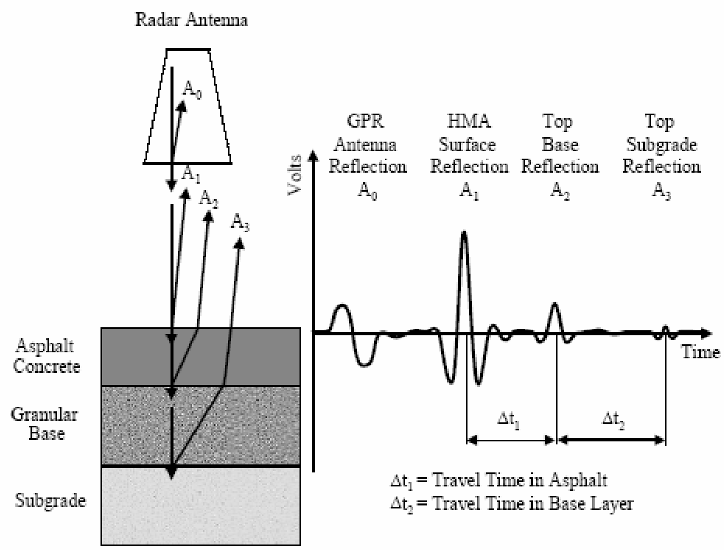

Figure 2: Typical air-coupled GPR profile (Berthelot et al., 2001)

The GPR measures the travel time, which is post-processed and converted to layer thickness. The thickness can be estimated if the relative dielectric constant is known.

LNEC's equipment has two pairs of air-launched (horn) antennas (1000 MHz and 1800 MHz), with a maximum penetration depth of 0.80 and 0.40 m, respectively.

GPR tests are undertaken along the same longitudinal profiles as FWD tests (Fontul and Antunes, 2001).

The cores are extracted after the GPR survey, in locations where the reflected signal is clear and constant along a certain distance.

GPR has become an important tool for pavement evaluation, since it allows for continuous measurement of the layer thickness (Fontul *et al.*, 2007) and therefore, a precise identification of changes in pavement structure, taking into account that historical data are in most of the cases erroneous or incomplete, while the cores give us only local information.

2.2. Interpretation of Results

Pavement layer stiffness moduli can be calculated from the FWD deflections using a backcalculation procedure, provided that the layer thickness is known.

Usually the layers thickness are fixed within this process, and assuming typical values for the Poisson's ratios, the deflection bowls are used for backcalculation of E moduli. Assuming a certain pavement structure, the values of the deflections are calculated for the FWD peak load and are compared with the measured deflections. Through an iterative process, the assumed E-moduli values are adjusted in order to reduce the difference between the deflections bowls, within a certain tolerance. The process is repeated in order to obtain a "theoretical deflection bowl" as close as possible to the deflection bowl measured in situ.

In most cases the backcalculation is performed using multilayer linear-elastic models which assume that the materials are linear elastic, homogeneous and isotropic. The load is considered static and consists of a vertical pressure, uniformly distributed over a circular area. Full friction is usually assumed at the interfaces between layers.

The main concern during this process is the large number of possible results. As the solution is not unique, several combinations of materials properties and layer's geometry can lead to the same answer, in terms of deflections under a certain load. Not always, the best deflection fitting corresponds to the more realistic pavement model. Therefore, it is essential to use some degree of engineering judgement to evaluate the results.

Missing or erroneous thickness data will cause unrealistic results of the backcalculation process. The more information available on pavement structure, the better the backcalculation results.

The pavement is quite heterogeneous, its variability reflects the combination of changes in various parameters that influence its behaviour along the road. Therefore for structural evaluation purposes the pavement is generally divided into homogeneous subsections. For a given homogeneous subsection, the pavement structural model can be set up for each test location or for a certain point corresponding to a "representative deflection bowl". This point will be considered to represent the pavement response observed in the homogeneous subsection (Antunes, 1993).

The representative deflection bowl will be used for the backanalysis of pavement layer moduli. Thus, the structural model set-up for the point where this deflection bowl was measured will be considered as representing the subsection. Alternatively, the interpretation of deflection measurements can be performed at every test point. Therefore, the application of GPR for pavement evaluation represents an important step forward, as it provides continuous information on layer thickness, for the bound and also unbound layers.

2.3. Artificial Neural Networks

General presentation.

Due to the large amount of data an efficient tool for the backcalculation is needed. Among the available methods the use of Backpropagation Artificial Neural Networks (ANN) is considered a promising approach (Fontul, 2004).

As in other fields of civil engineering, the use of artificial neural networks in pavement analysis has increased during the last years. Artificial Neural Networks (ANN) are biologically inspired. They have the ability to act as functional approximators that can "learn" a functional mapping when repetitively exposed to examples of that mapping (Hect-Nielsen, 1989).

ANNs are interconnected assemblages of simple computational elements called "neurons" (Meier *et al.*, 1997). Each neuron receives stimuli from their connections, then the combined input is modified by an *activation function* (simple mathematic operation) and finally the output value is passed by to another neuron through connections. A weight is associated to each connection between neurons and represents the importance of the connection. The process by which a neural network adapts to the intended environment is called “training” and consists of the modification of the weight of the connections between the neurons.

The backpropagation ANN enables a certain control of the response as their training is “supervised”, is performed using examples and consequently the answer will be within the range of values used for training. They consist in minimum of three layers, one input and one output layer and at least one “hidden” layer (see Figure 3). The number of neurons in the first and the last layer is equal to the number of input and output parameters. This process of training in the case of back-propagation ANN consists of three distinct phases. Fist, all the connections are assigned arbitrary weights, generally “small” random numbers. In the first phase (forward propagation) of training the input signals are propagated through the hidden layers until the output neurons, resulting in a collection of values. In the second phase the “errors” are calculated. They are given by the difference between the "expected" outputs and the values calculated in the fist phase (forward propagation). Once the errors for each neuron are known, they are back-propagated during the third phase (backward propagation). In this phase the weights of the connection are corrected in order to achieve an improvement of the network response. This process is repeated as many times as necessary to obtain a satisfactory ANN response. The network architecture has to be the best combination between accuracy and training speed. After the training process is finished, it is convenient to test the ANN, through a process called validation.

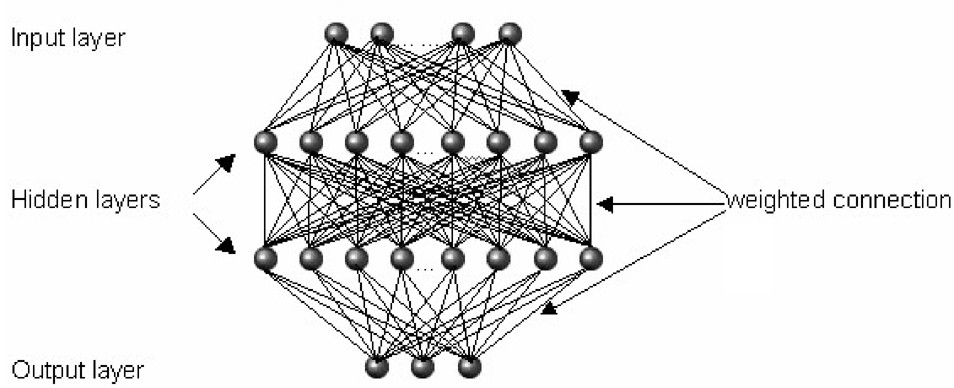

Figure 3. Artificial Neural Network structure

Application of ANN for Interpretation of NDT Results

An ANN can be “trained” to determine the corresponding pavement layer moduli from deflection basins, based on a database of FWD test results (Meier *et al.*, 1997). The main objective is to perform the interpretation of all FWD test results and consequently to evaluate the pavement structure in all FWD test points. For this purpose, the GPR results are used as an average value of layer thickness over a 5 m interval around each FWD test point. For an efficient backcalculation an ANN is trained (using synthetic deflections) and than used for layer moduli estimation based on measured deflections and layer thickness.

Using the response model selected for the pavement under consideration (generally multi-layer linear elastic model) synthetic deflections are calculated for the pavement structure under study. Variations in pavement structure parameters have to be considered in order to uniformly cover the applicable range of values. In this way, data sets of deflections, layer thickness and elastic moduli are obtained. During training, deflections and layer thicknesses from this database are considered as inputs, while the corresponding elastic moduli represent the target outputs (Fontul 2004).

A computer program "Redes 3" for the automatic calculation of the backpropagation multilayer neural network, developed at LNEC (Marcelino, 1998) has been used. This program allows for selecting the characteristics of the neural network, the limits of the parameters as well as the type of transfer function and training technique to be used.

3. CASE STUDY

3.1. General Presentation

An application of Artificial Neural Network technique for airport pavement bearing capacity evaluation is presented herein. This example refers to structural assessment of an airport runway where FWD and GPR tests were performed. The pavement is flexible, composed of bituminous wearing course, binder course and base layer, and unbound granular base and sub-base, over the subgrade soil. The runway pavement was built in 1965 and is 2400 m long and 45 m wide. Since construction, the initial structure has suffered two major rehabilitations in 1980 and 1990 as well as several local repairs.

The present pavement structure comprises 0.30 m of unbound aggregate base, 0.10 m of bituminous macadam base and three layers of asphalt concrete, which correspond to the successive construction phases and have variable thickness.

FWD tests were performed along 7 longitudinal profiles parallel to the center line (CL). In each test point three drops were performed from the third height in order to obtain a peak load of 150 kN, applied on a 450 mm diameter loading plate. Deflections were measured at 0 m (D_0), 0.30 m (D_1), 0.45 m (D_2), 0.60 m (D_3), 0.90 m (D_4), 1.20 m (D_5) and 1.80 m (D_6) distances from the center of the loaded area, and normalised for 150 kN load.

GPR tests were undertaken along 6 longitudinal profiles, the same as FWD tests except the CL (due to the proximity of metal parts that affect the results). The measurements were performed with both horn antenna pairs (1 GHz and 2 GHz) and the number of scans per meter used was 4.

The case presented herein corresponds to the testing profile located at 3 m from the CL on the right side of the runway (3mR). The deflections obtained, as well as the GPR file, clearly show the transition between two different pavement structures (around 750 m), that correspond to the distinct overlay thicknesses applied in 1990 (see Figure 4).

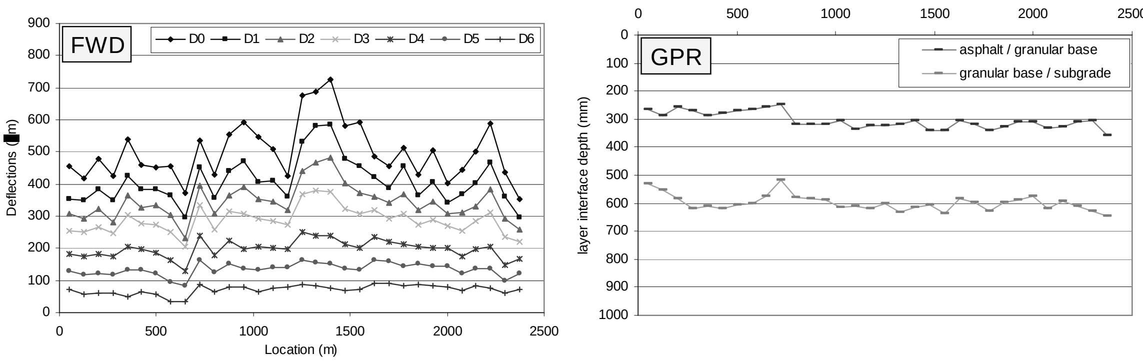

Figure 4. FWD and GPR results pre-processed for ANN inputs (D0 to D6 and h1, h2)

3.2. Data Analysis

A division in homogeneous subsections was performed based on the normalised deflections, using the cumulative difference method. Two distinct subsections were identified: zone 1 (0 to 750 m from END 10) and zone 2 (750 m to 2400 m).

A three-layered flexible pavement structure overlaying a bedrock was analysed. The structure consists of a bituminous concrete layer, a base layer and a soil subgrade. The ranges of pavement layer properties adopted for the ANN training are presented in Table 1.

Table 1. Training database – pavement structure parameters

Layer	Bituminous			Base			Subgrade			Bedrock	
Parameter	E_1	h_1	ν_1	E_2	h_2	ν_2	E_3	h_3	ν_3	E_4	ν_4
Units	MPa	m		MPa	m		MPa	m		MPa	
Minimum value	1000	0.22	0.40	200	0.28	0.35	80	2.00	0.35	500	0.35
Maximum Value	6000	0.38	0.40	500	0.32	0.35	240	3.50	0.35	500	0.35

Legend:
E_1, E_2, E_3, E_4, – Modulus of bituminous layer, base layer, subgrade layer and bedrock;
h_1, h_2, h_3, - Layer thickness of bituminous layer, base layer and subgrade layer;
ν_1, ν_2, ν_3, ν_4, – Poisson's ratio of bituminous layer, base layer, subgrade layer and bedrock.

Synthetic deflections were obtained based on various pavement structures, resulting from combinations of layers thickness and moduli (106572 datasets were produced).

A four-layer, feed forward ANN network was used. The network consists of an input layer and an output layer separated by two hidden layers, each of them with 15 neurons (9/15/15/4). During training, the inputs were the deflections (D_0 to D_6) and the pavement layer thickness

(h_1 and h_2) and the outputs were the layer moduli (E_1, E_2, and E_3) and the subgrade thickness (h_3).

When using this methodology, it is important to perform the interpretation of a few examples of FWD test results (using classic approach) before training the ANN in order to obtain feedback on the expected moduli, information needed to set-up the variation range. Taking into account the temperature during testing, the range for the asphalt modulus may differ from the values expected for the design temperature.

The results obtained for E moduli using ANN are presented in Figure 5 together with the ones normally obtained through classic approach, namely one representative test point per homogeneous subsection.

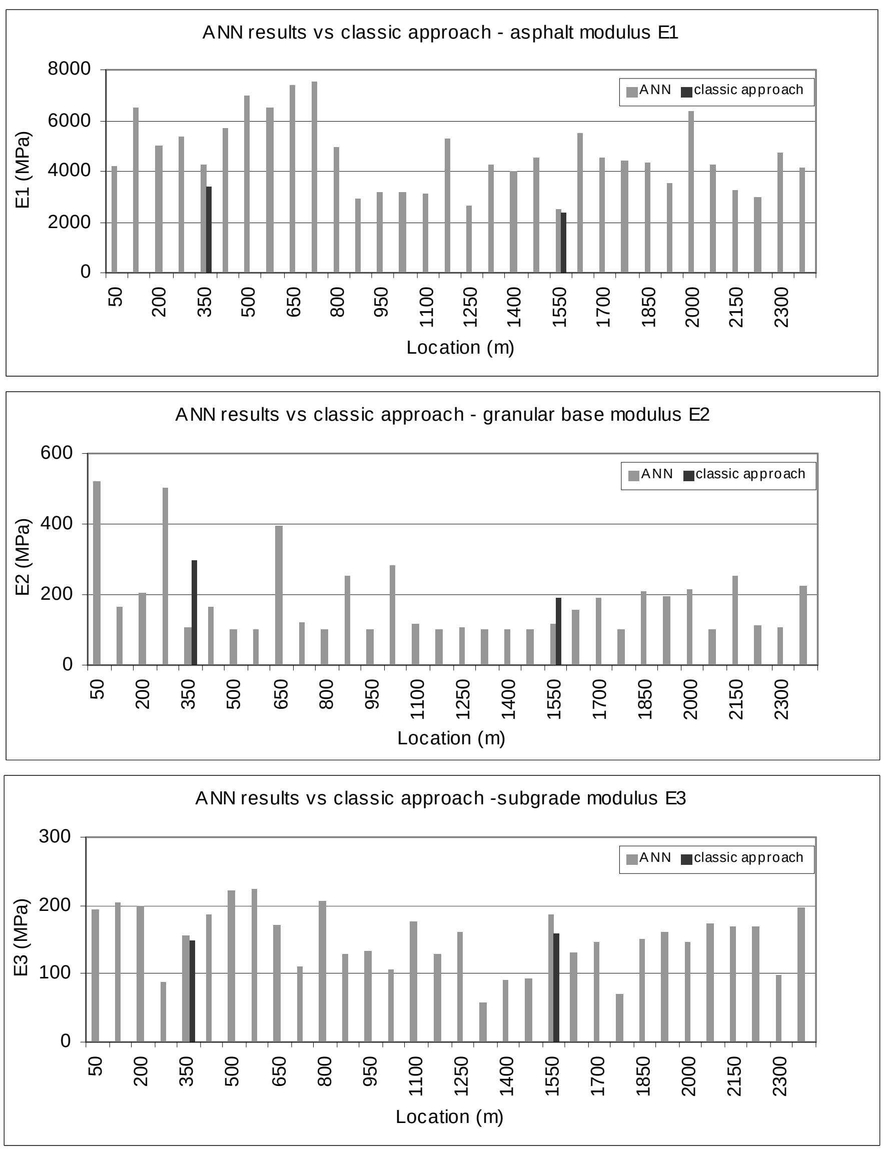

Figure 5. Comparison between ANN results and classic approach

The results obtained using ANN are realistic and are not very different from the ones obtained using a classic approach. The poorer correlation in case of E_2 moduli is attributed to the pavement structure itself. As it is a structure with thick bituminous layers, the base layer has a reduced influence on pavement's response to FWD loads. Therefore, a large variation of E_2 moduli will result in smaller changes in deflections.

4. FINAL REMARKS

The proposed method aims at combining the FWD and GPR data and at processing the results in an efficient way. The main objective is to perform the interpretation of all FWD test results and consequently to evaluate the pavement structure in all FWD test points.

The application of the proposed methodology to a real case study has proven that the use of Artificial Neural Networks (ANN) in backanalysis of FWD test results presents important advantages. The use of ANN on one hand, it may allow for a drastic reduction in computation time and on the other hand, the values obtained for layer elastic moduli can be more “realistic”, since the answer is derived from the data used in the training. The applicability of ANN is limited to the test conditions and pavement structure used for training.

The type of structure model and the ANN architecture must be carefully chosen for each case under study. Therefore, the applicability of the proposed method to other type of pavements such as rigid or composite pavements is not straightforward.

The work presented herein addressed the use of a multilayer linear elastic programme for training the ANN. It is acknowledged that this type of response model is a simplification of the pavement’s behaviour. However, the proposed methodology can be applied using more sophisticated pavement models, in order to take into account the viscoelastic behaviour of asphalt materials or the non-linear response of soils and granular materials.

The use of ANN could also be an interesting approach to derive pavement’s residual life directly from measured deflection basins, especially for studies at network level.

The use of ANN in other fields associated with pavement modelling is also a topic for future development. An example is to use ANN for the prediction of development of pavement deterioration in time, using data from Long Term Pavement Performance Studies.

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