Airfield Pavement Deterioration Assessment Using

Stress-Dependent Neural Network Models

Kasthurirangan Gopalakrishnan, Halil Ceylan, and Alper Guclu

Department of Civil & Environmental Engineering, Iowa State University, 353 Town Engineering Building, Ames, IA 50011-3232, USA

Abstract

In this study, an Artificial Neural Networks (ANN) based approach was employed to backcalculate the asphalt concrete and non-linear stress-dependent subgrade moduli from Non-Destructive Test (NDT) data acquired at the Federal Aviation Administration's National Airport Pavement Test Facility (NAPTF) during the full-scale traffic testing. The ANN models were trained with results from an axi-symmetric finite-element pavement structural model. Using the ANN-predicted moduli based on the NDT test results, the relative severity effects of simulated Boeing 777 (B777) and Boeing 747 (B747) aircraft gear trafficking on the structural deterioration of NAPTF flexible pavement test sections were characterized. The results indicate the potential of using lower force amplitude NDT test data for routine airport pavement structural evaluation as long as they generate sufficient deflections for reliable data acquisition. Thus, NDT tests which employ force amplitudes at prototypical aircraft loading may not be necessary to evaluate airport pavements.

Keywords: Artificial neural networks; Non-destructive test; NAPTF; Nonlinear; Airport flexible pavement systems

1. Introduction

The National Airport Pavement Test Facility (NAPTF) is located at the Federal Aviation Administration's (FAA) William J. Hughes Technical Center near Atlantic City International Airport, New Jersey, USA. It was constructed to support the development of advanced mechanistic-based airport pavement design procedures based on sound theoretical principles and with models verified from appropriate full-scale test data.

The first series of test pavements, referred to as Construction Cycle 1 (CC-1), consisted of nine instrumented test pavements (six flexible and three rigid) that were 18.3 m (60 ft) wide and total 274.3 m (900 ft) in length. The nine test pavements were built on three different subgrade materials: low-strength (target California Bearing Ratio [CBR] of 4), medium-strength (target CBR of 8), and high-strength (target CBR of 20).

The NAPTF was constructed to generate full-scale testing data especially to support the investigation of the performance of airport pavements subjected to complex gear loading configurations of New Generation Aircraft (NGA) such as the Boeing 777. During the first series of traffic tests at NAPTF, a simulated six-wheel Boeing 777 (B777) landing gear in one lane and a four-wheel Boeing 747 (B747) landing gear in the other lane were trafficked simultaneously until the test pavements were deemed failed. Non-Destructive Tests (NDT) using both Falling Weight Deflectometer (FWD) and Heavy Weight Deflectometer (HWD) were conducted to document the uniformity of pavement and subgrade construction as well as to monitor the effect of full-scale trafficking on pavement response and performance over time.

McQueen *et al.* (2001) analyzed the flexible pavement NDT data acquired at the NAPTF by evaluating the NDT response with force amplitude and by backcalculating the subgrade modulus (using an elastic layered program-based backcalculation software) from the NDT data. To test if the NDT response is nonlinear with increasing force, same location FWD data at four loads (40-kN, 60-kN, 82-kN, and 115-kN) and HWD data at three loads (53-kN, 107-kN, and 160-kN) were evaluated. It was found that both the Impulse Stiffness Modulus (ISM = ratio of applied force to maximum deflection of load plate) and backcalculated subgrade modulus were relatively constant with FWD and HWD force amplitude. Similar results were obtained for HWD tests conducted at center slab on instrumented rigid pavements at Denver International Airport (DIA) (Lee et al., 1998).

Based on these observations (linear load-response behavior) for both flexible and rigid airport pavements, McQueen *et al.* (2001) suggested that using NDT force amplitudes at prototypical aircraft loading may not be necessary to evaluate airport pavements. It was further suggested that airport pavements can be evaluated satisfactorily with lighter load devices, such as the FWD, provided sufficient response is obtained to allow for reliable sensor recordation.

Thus, based on the results from the sensitivity studies at the NAPTF and DIA, the amplitude of the impulse load does not seem to be critical provided the generated deflections are within the limits of all deflection sensors. The key factors that will determine the allowable range of impulse loads are pavement layer thicknesses and material types. Thus, unless the pavement is a very thick Portland Cement Concrete (PCC) or Asphalt Concrete (AC) overlaid PCC structure, most FWD devices will be

acceptable since they will be able to generate sufficient deflections for reliable data acquisition (FAA 2004).

To verify this, a study was undertaken to backcalculate the AC and subgrade moduli from FWD data acquired at NAPTF during the full-scale traffic testing using an Artificial Neural Networks (ANN) based approach. The results could be used to examine the damaging effect of B777 and B747 trafficking on the structural condition (backcalculated moduli) of NAPTF flexible pavement sections.

2. ANN based backcalculation models

The Elastic Layered Programs (ELPs) used in the analysis and design of flexible pavements consider the pavement as an elastic multi-layered media, and assume that pavement materials are linear-elastic, homogeneous and isotropic. However, the unbound granular materials and fine-grained subgrade soils, referred to as pavement geomaterials, do not follow a linear stress-strain behavior under repeated traffic loading. The non-linearity or stress-dependency of resilient modulus for unbound granular materials and cohesive fine-grained subgrade soils has been well established (Brown and Pappin 1981, Thompson and Elliot 1985, Garg *et al.* 1998). Unbound aggregates exhibit stress hardening type behavior whereas fine-grained subgrade soils show stress-softening type behavior.

Previous research studies have shown the non-linearity of underlying pavement layers at the NAPTF. Gomez-Ramirez and Thompson (2002) reported the presence of material non-linearity at NAPTF by separately analyzing the individual layer compression from Multi-Depth Deflectometer (MDD) readings. Garg and Marsey (2002) have similarly observed the stress-dependent nature of the granular and subgrade layers in NAPTF flexible test sections. Therefore, pavement structural models which can take into account non-linear geomaterial characterization, such as the ILLI-PAVE finite element program (Raad and Figueroa 1980) need to be employed to perform NAPTF pavement structural analysis and more realistically predict pavement responses needed for mechanistic based pavement design.

A study was undertaken to backcalculate the non-linear pavement layer moduli from NAPTF flexible pavement FWD data using ANN. ANNs are increasingly being used to solve resource-intensive complex problems as an alternative to using more traditional techniques such as regression methods. Over the years, ANNs have emerged as successful computational tools for studying a majority of pavement engineering problems (Meier and Rix, 1995; Meier et al, 1997; Gucunski and Krstic 1996; Khazanovich and Roesler 1997; Kim and Kim 1998; Ceylan 2002; Ceylan et al 2004). In the development of the new mechanistic-empirical pavement design guide for the American Association of State Highway and Transportation Officials (AASHTO), ANNs have been recognized as non-traditional, yet very powerful computing techniques and were used in preparing the concrete pavement analysis package.

Recent research studies at the Iowa State University and University of Illinois have focused on the development of ANN based forward and backcalculation type highway flexible pavement analysis models to predict critical pavement responses and layer moduli, respectively (Ceylan *et al.* 2005). Gopalakrishnan *et al.* (2006) and Gopalakrishnan and Thompson (2004) successfully demonstrated the ANN-based

approach for backcalculating airport flexible pavement layer moduli from HWD test data, specifically targeted towards the study of NAPTF flexible pavement sections.

In the current study, ANN models that were originally developed and validated for predicting the pavement layer moduli from the 40-kN (9,000-lb) FWD deflection basins of highway flexible pavements, were used in backcalculating flexible pavement layer moduli from 40-kN (9,000-lb) FWD data acquired during full-scale traffic testing at the NAPTF. These ANN models have been comprehensively trained and tested over a wide range of pavement layer properties and are therefore expected to produce realistic backcalculation results for NAPTF test sections.

The FWD/HWD test is conducted to evaluate the structural integrity and load-carrying capacity of existing pavements. Pavement deflection profiles obtained from the FWD/HWD measurements are used for backcalculating the pavement layer stiffnesses which can be used to estimate pavement remaining life. Currently, there are no closed-form solutions to accomplish backcalculation. Presently, elastic layered analysis is commonly used in most backcalculation software to predict the layer moduli typically using a deflection basin-matching approach. In this approach, layer moduli are initially assumed and theoretical surface deflections are computed. Through a series of iterations, the layer moduli are changed, and the computed deflections are then compared to the measured deflections until a match is obtained within tolerance limits. This approach has several disadvantages and does not result in unique layer moduli values as there can be more than one combination of layer moduli to achieve the match between theoretical and measured surface deflections.

Although ANN-based models have been successfully used in the past for backcalculating pavement moduli from FWD data (Meier *et al.* 1997), they did not account for realistic stress-sensitive geomaterial properties as ELP-generated synthetic database was used to train the ANN. Therefore, the ILLI-PAVE finite element program, which can take into account non-linear stress-dependent geomaterial properties, was utilized to generate the ANN training dataset to accurately predict pavement layer moduli from realistic FWD deflection profiles.

3. Generation of ANN training and testing dataset

Developed at the University of Illinois (Raad and Figueroa 1980), ILLI-PAVE is an axisymmetric finite element (FE) program commonly used in the structural analysis of flexible pavements. It models the pavement as a two-dimensional axisymmetric solid of revolution and employs nonlinear stress-dependent models and failure criteria for granular materials and fine-grained soils. Numerous research studies have validated that the axisymmetric ILLI-PAVE model provides a realistic pavement structural response prediction for highway and airfield pavements under circular wheel loading (Thompson and Elliot 1985, Thompson 1992, Garg *et al.* 1998).

The ILLI-PAVE finite element model was therefore used in this study as an advanced structural model for solving flexible pavement surface deflections and other critical pavement stresses and strains under applied wheel loading. The goal was to establish a database of ILLI-PAVE response solutions that would eventually constitute the training and testing data sets for developing ANN-based structural models for the rapid backcalculation analyses.

A generic three-layer flexible pavement structure consisting of AC surface layer, unbound aggregate base layer, and subgrade layer was modeled in ILLI-PAVE. The top surface AC layer was characterized as a linear elastic material with Young's Modulus, E_{AC}, and Poisson ratio, ν. The K-θ model (Hicks and Monismith 1971) was used as the non-linear characterization model for the unbound aggregate layer:

$$E_R = K \left(\theta / p_o \right)^n \tag{1}$$

where E_R is resilient modulus, $\theta = \sigma_1 + \sigma_2 + \sigma_3 = \sigma_1 + 2\sigma_3 =$ bulk stress, p_0 is the unit reference pressure (1 kPa or 1 psi) used in the model to make the stresses non-dimensional, and K and n are multiple regression constants obtained from repeated load triaxial test data on granular materials. Based on the work of Rada and Witczak (1981) with a comprehensive granular material database, K and n model parameters can be correlated to characterize the non-linear stress dependent behavior with only one model parameter using the following equation (Rada and Witczak 1981) ($R^2 = 0.68$; SEE = 0.22):

$$Log_{10}(K) = 4.657 - 1.807 \cdot n \tag{2}$$

Accordingly, good quality granular materials, such as crushed stone, show higher K and lower n values, whereas the opposite applies for lower quality aggregates. Following the study by Rada and Witczak (1981), the K-values used typically ranged from 20.7 MPa (3 ksi) to 82.7 MPa (12 ksi) and the corresponding n-values were obtained from equation 2.

Fine-grained soils were considered as "no-friction" but cohesion only materials and modeled using the commonly used bi-linear model (Thompson and Elliot 1985) for resilient modulus characterization:

$$E_R = E_{Ri} + K_1.(\sigma_d - \sigma_{di}) \quad for \, \sigma_d < \sigma_{di}$$
$$E_R = E_{Ri} + K_2.(\sigma_d - \sigma_{di}) \quad for \, \sigma_d > \sigma_{di} \tag{3}$$

where E_{Ri} is the breakpoint resilient modulus, σ_d is the breakpoint deviator stress ($\sigma_d = \sigma_1 - \sigma_3$), σ_{di} is the breakpoint deviator stress, and K_1 and K_2 are statistically determined coefficients from laboratory tests. As indicated by Thompson and Elliot (1985), the value of the resilient modulus at the breakpoint in the bilinear curve, E_{Ri}, can be used to classify fine-grained soils as being soft, medium or stiff. The E_{Ri} is the main input for subgrade soils in ILLI-PAVE. The bilinear model parameters were set to default values.

Therefore, asphalt concrete modulus, E_{AC}, granular base K-θ model parameter K, and the subgrade soil break point deviator stress, E_{Ri}, in the bilinear model were used as the layer stiffness inputs for all the different flexible pavement ILLI-PAVE runs. The 40-kN (9-kip) wheel load was applied as a uniform pressure of 552 kPa (80 psi) over a circular area of radius 152 mm (6 in) simulating the FWD loading.

Backpropagation type artificial neural network models (Haykin 1999) were trained in this study with the ILLI-PAVE synthetic solutions database and were used as

rapid analysis tools for predicting flexible pavement layer moduli. Backpropagation type neural networks were used to develop two ANN structural models with different network architectures for predicting the pavement layer moduli (E_{AC} and E_{Ri}) using the FWD deflection data and pavement layer thicknesses. A neural network architecture with two hidden layers was exclusively chosen in accordance with the satisfactory results obtained previously with such networks considering their ability to better facilitate the nonlinear functional mapping (Ceylan 2002).

Several network architectures with two hidden layers were trained. Overall, the training and testing mean squared errors (MSEs) decreased as the networks grew in size with increasing number of neurons in the hidden layers. The testing MSEs were, in general, slightly lower than the training ones. The error levels for both the training and testing sets matched closely when the number of hidden nodes approached 60.

In this study, the 8-60-60-1 (eight inputs, two hidden layers with 60 hidden neurons each, and one output) architecture was chosen as the best architecture for the ANN models based on its lowest training and testing MSEs in the order of 1×10^{-4} (corresponding to a Root Mean Squared Error [RMSE] of 0.3%) for both output variables, E_{AC} and E_{Ri}. Since the objective is to backcalculate E_{AC} and E_{Ri} from field-measured FWD deflection data, the eight inputs in the best-performance ANN architecture include the six FWD surface deflections (D_0, D_8, D_{12}, D_{18}, D_{24}, D_{36}, D_{48}, D_{60}, and D_{72}) collected at the drop location (0), and at radial offsets of 254-mm (12-in.), 610-mm (24-in.), 914-mm (36-in.), 1219-mm (48-in.), and 1524-mm (60-in.), and two known pavement layer thicknesses; AC layer (h_{AC}) and granular layer (h_{GB}). The same ANN architecture was used for predicting both E_{AC} and E_{Ri}.

Figure 1 depicts the prediction ability of the 8-60-60-1 network at the 10,000[th] training epoch. Average absolute errors (AAEs) were calculated as sum of the individual absolute errors divided by the 1,500 independent testing patterns. The AAE for the AC layer moduli was a low 1.25% while the AAE for the subgrade breakpoint moduli, E_{Ri}, was 3.46%. Note that the AC moduli is strongly related to the maximum FWD surface deflection, D_0, while the subgrade moduli is largely a function of FWD surface deflection at offsets greater than 914 mm (36 in.). Note that the magnitude of FWD surface deflections decreases with increasing radial offsets and so does the relative accuracy of measurements. As a result, the prediction accuracy for AC moduli is generally higher compared to subgrade moduli.
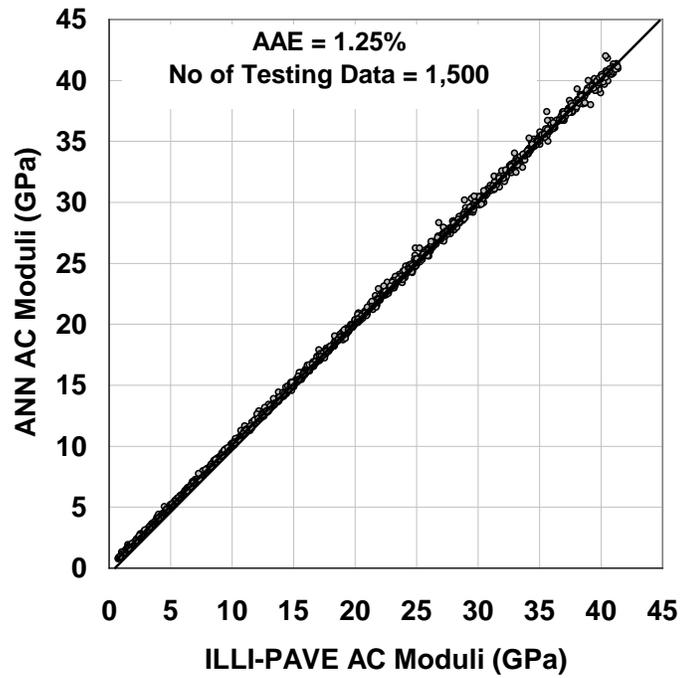
(a)
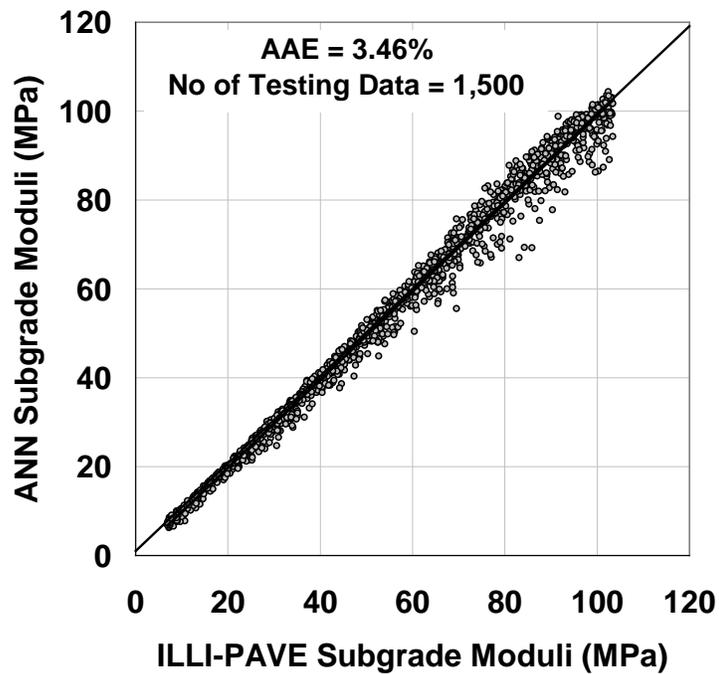
(b)

Figure 1. Prediction performance of the ANN backcalculation models: (a) AC modulus, (b) subgrade modulus.

As shown in figure 1, almost all 1,500 ANN predictions fell on the line of equality for the two pavement layer moduli thus indicating a proper training and excellent performance of the ANN models. The development of ANN backcalculation models employed in this study are discussed in detail by Ceylan *et al.* (2004).

A major benefit of applying the developed ANN based backcalculation techniques in routine FWD evaluations will come from the very high-speed data processing and analyses that can even be performed in the field. The ANN models developed in this study are about two times faster than the ILLI-PAVE FE model solutions and they do not require lengthy and detailed finite-element pre- and post-processing tasks. The rapid prediction ability of the ANN backcalculation models (50,000 FWD deflection basins can be analyzed in less than a second) makes them perfect tools for analyzing the FWD deflection data, and thus assessing the condition of the pavement sections, in real time during the field tests. To fulfill the objectives of this study, the developed ANN models were applied to the field FWD data acquired at the NAPTF during full-scale traffic testing of flexible pavement sections using six-wheel and four-wheel heavy aircraft gear loading. A description of the NAPTF pavement testing program follows.

4. NAPTF flexible pavement sections

The first series of NAPTF test pavements, referred to as Construction Cycle 1 (CC-1), consisted of nine instrumented test pavements (six flexible and three rigid) that were 18.3 m (60 ft) wide and total 274.3 m (900 ft) in length. In this study, the following medium-strength subgrade flexible pavement test sections were considered: (a) MFC – a conventional granular base flexible pavement, and (b) MFS – an asphalt-stabilized base flexible pavement. As-constructed cross-sectional views of these two test items considered in this study are shown in figure 2.
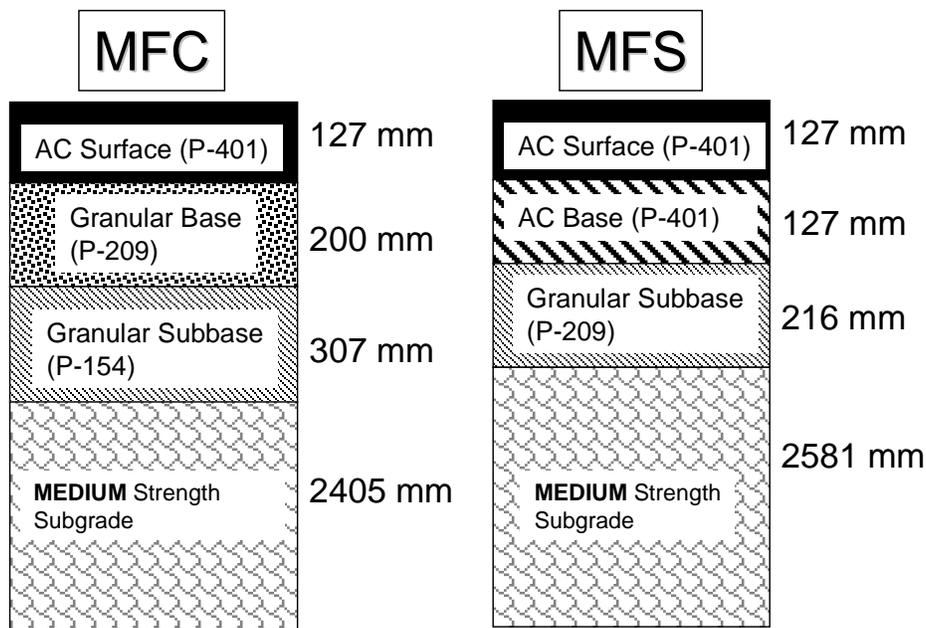

Figure 2. Cross-sectional views of NAPTF medium-strength flexible pavement sections.

The items P-209 (crushed stone), P-154 (grey quarry blend fines) and P-401 (plant mix bituminous pavement) are as per standard specifications detailed in the FAA Advisory Circular No. AC 150/5370-10. The P-401 was used in both the AC surface layer as well as in the stabilized layer in the MFS section. A CL-CH soil classification (ASTM Unified Soil Classification System) material known as Dupont Clay (DPC) was used for the medium-strength subgrade. The naturally-occurring sandy-soil material (SW-SM soil classification) at the NAPTF site underlies each subgrade layer. The gradation information, laboratory compaction properties and material characterization test results for the subgrade soils, P-209, and P-154 geomaterials are contained in the FAA's materials database (accessible for download at the FAA Airport Technology website: www.airporttech.tc.faa.gov) (Hayhoe and Garg 2001).

5. NAPTF traffic testing

The NAPTF was dedicated on April, 1999 followed by a 10-month period of verification, shakedown, and pavement response testing. The first series of traffic tests, referred to as CC-1 traffic testing, began in February 2000 and was completed in September 2001.
During CC-1 traffic testing, a six-wheel dual-tridem (B777) landing gear, with 1372-mm (54-in) dual spacing and 1448-mm (57-in) tandem spacing was loaded on the north wheel track (LANE 2) while the south side (LANE 5) was loaded with a four-wheel dual-tandem (B747) landing gear having 1118-mm (44-in) dual spacing and 1473-mm (58-in) tandem spacing.

The test machine and the gear configurations used during the first round of traffic testing are shown in figure 3. The wheel loads were set to 20,412 kg (45,000 lbs) each and the tire pressure was 1,295 kPa (188 psi). The traffic speed was 8 km/h (5 mph) throughout the traffic test program. To realistically simulate transverse aircraft movements, a wander pattern consisting of a fixed sequence of 66 vehicle passes (33 traveling in the east direction and 33 traveling in the west direction), arranged in nine equally spaced wander positions (or tracks) at intervals of 260 mm (10.25 in), was used during traffic testing.
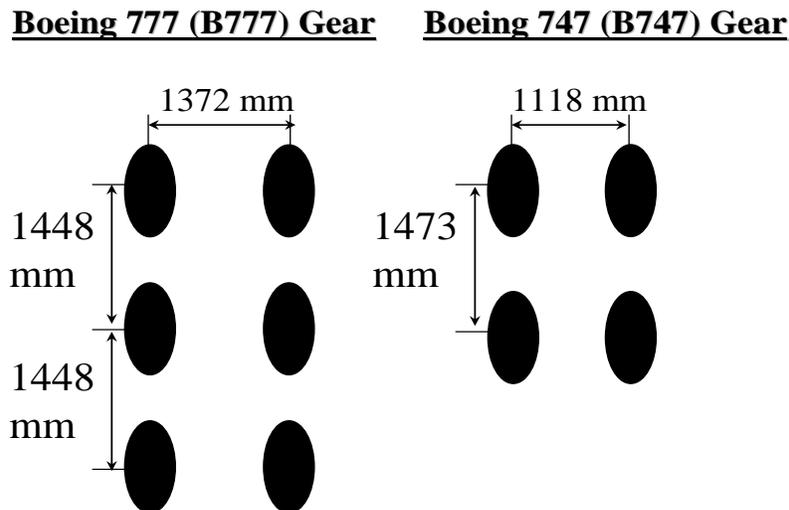
Boeing 777 (B777) Gear   **Boeing 747 (B747) Gear**

Figure 3. Simulated aircraft test gears used in NAPTF traffic testing.

The NAPTF failure criterion was the one established in the U.S. Army Corps of Engineers' (US COE) Multi-Wheel Heavy Gear Load (MWHGL) tests (Ahlvin et al 1971). Failure is defined as the presence of at least 25.4-mm (1-in) surface upheaval adjacent to the traffic lane. This is linked to a structural or shearing failure in the subgrade. The NAPTF test sections were trafficked until they were deemed failed.

6. Non-destructive testing

Recent advances in hardware and software technology have significantly improved NDT equipment, data collection, and analysis software. There are several advantages to using NDT, in lieu of, or supplement traditional destructive tests in airport pavements. Most important, is the capability to quickly gather data at several locations while keeping a runway, taxiway, or apron operational during these 2-minute to 3-minute tests, provided the testing is under close contact with Air Traffic Control. Nondestructive tests are economical to perform and data can be collected at up to 250 locations per day. The FWD/HWD equipment measures pavement surface response (i.e., deflections) from an applied dynamic load that simulates a moving wheel (FAA 2004).

The deflection data that are collected with FWD/HWD equipment can provide both qualitative and quantitative data about the strength of a pavement at the time of testing. The raw deflection data directly beneath the load plate sensor provides an indication of the strength of the entire pavement structure. Likewise, the raw deflection data from the outermost sensor provides an indication of subgrade strength (FAA 2004). Many studies have addressed the interpretation of FWD/HWD pavement deflection measurements as a tool to characterize pavement-subgrade systems (Bush and Baladi 1989, Tayabji and Lukanen 2000).

Nondestructive tests using both FWD and HWD were conducted on NAPTF flexible pavement test sections at various times. In this study, the focus is on HWD test results. The HWD tests were conducted using a KUAB 2m HWD device acquired by the FAA. The FAA HWD equipment was also configured with a 30.5-cm (12-in) loading plate and a pulse width of 27-30 msec was used. The HWD tests were conducted at nominal force amplitudes of 53.4-kN (12,000-lb), 106.7-kN (24,000-lb), and 160-kN (36,000-lb). The deflections were measured at radial offsets of 0-mm (D_0), 305-mm (D_1), 610-mm (D_2), 914-mm (D_3), 1219-mm (D_4), and 1524-mm (D_5) intervals from the center of the load.

The location and orientation of HWD test lanes are illustrated in figure 4. The HWD tests were performed on the untrafficked C/L and on the B777 and B747 traffic lanes (LANE 2 and LANE 5). The HWD test sequences were repeated at 3-m (10-ft) intervals along the test lanes. The HWD test results can be downloaded from the FAA Airport Technology Branch website.
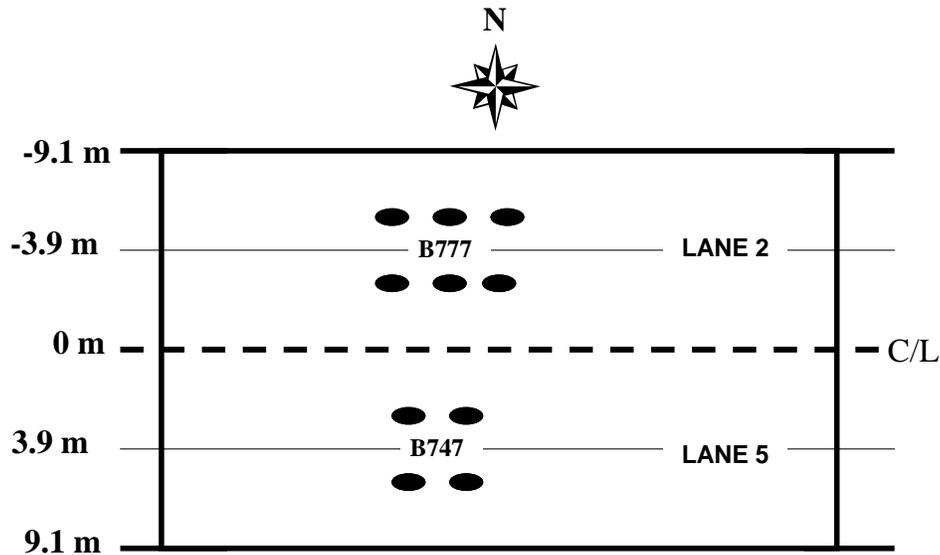
Figure 4. Schematic of NDT test locations.

7. NAPTF pavement structural characterization using ANN models

To demonstrate the applicability of the ANN-based methodology for analyzing the NAPTF flexible pavement sections and to further validate the ANN models, the models were examined using the actual NDT data acquired at the NAPTF during traffic testing. The approach was to predict pavement layer moduli using the ANN models and compare ANN results to those obtained using a conventional ELP-based backcalculation program.

Distress modes normally considered in flexible pavement analysis and design are fatigue cracking, rutting, and low-temperature cracking. Classical flexible pavement design procedures are based on limiting the vertical compressive strain on top of the subgrade (subgrade rutting failure criteria) and the horizontal tensile strain at the bottom of the lowest AC layer (AC fatigue failure criteria). In this paper, the focus is on studying the comparative effect of repeated aircraft trafficking on airfield pavement layer moduli, especially the AC moduli and subgrade moduli.

The FAA's backcalculation software, BAKFAA, was developed under the sponsorship of the FAA Airport Technology Branch and is based on the LEAF ELP (Hayhoe 2002). In this program, the pavement layer moduli and subgrade moduli are adjusted to minimize the root mean square of the differences between NDT sensor measurements and the LEAF-computed deflection basin for a specified pavement structure. A standard multidimensional simplex optimization routine is then used to adjust the moduli values (McQueen *et al.* 2001). A stiff layer with a modulus of 6.9 GPa (1,000,000 psi) and a Poisson's ratio of 0.50 was used in backcalculation. Based on the as-constructed conditions, the stiff layer was set at 3 m (10 ft) for the medium-strength test sections.

The results from laboratory resilient modulus tests (adaptation of AASHTO T292) conducted on NAPTF subgrade soil samples indicated that the modulus for medium-

strength subgrade is 86 MPa (12,500 psi) at a confining stress of 41 kPa (6 psi) and a deviator stress of 14 kPa (2 psi). At a deviator stress of 41 kPa (6 psi), the resilient modulus is 62 MPa (9,000 psi) for medium-strength subgrade. These results are based on laboratory testing of subgrade soil samples obtained from test pits before the NAPTF test sections were opened to trafficking (Hayhoe and Garg 2001, Gopalakrishnan 2004).

  The ANN backcalculation models described in this paper have been developed for backcalculating pavement layer moduli from 40-kN (9,000-lb) FWD deflection basins. Since 40-kN (9,000-lb) FWD tests were not conducted during the course of NAPTF trafficking, the 53.4-kN (12,000-lb) HWD deflection basins were normalized to 40-kN (9,000-lb) loading as the deflections were fairly linear in this range. Using these deflection basins collected during the course of trafficking, the changes in backcalculated pavement layer moduli with increasing number of traffic load repetitions could be studied.

  The temperature of the AC layer at the time of FWD testing has a significant influence on the surface deflections as well as the backcalculated AC modulus. During the construction of NAPTF facility, static temperature sensors were installed at different depths within the pavement to record the pavement temperatures at different times of the day. The variations in AC layer mid-depth temperatures during trafficking are shown in figure 5 for both MFC and MFS test sections.
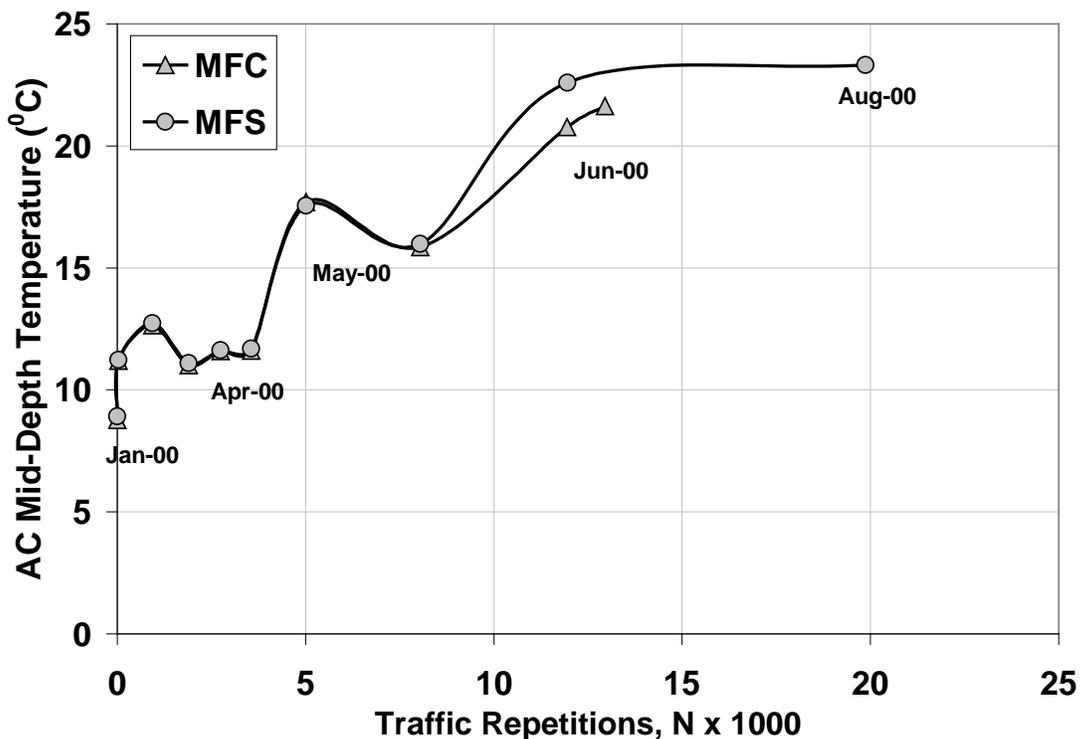

Figure 5. Variations in asphalt concrete pavement temperature during NAPTF traffic testing.

The variations in ANN-based backcalculated AC moduli (E_{AC}) with the number of traffic load repetitions (N) are shown in figure 6 for MFC and MFS test sections. The results are shown for the B777 and B747 traffic lanes as well as the untrafficked Centerline (C/L). Note that the changes in E_{AC} values in the untrafficked C/L were mainly due to the changes in the AC temperature. With increasing traffic load repetitions, the traffic lane E_{AC} values were distinguishably lower than the C/L values, especially in the MFC test section, indicating loss of stiffness resulting from trafficking. Also, in the MFC test section, the B747 traffic lane E_{AC} values were consistently lower than those obtained from the B777 traffic lane indicating relative severity effects.
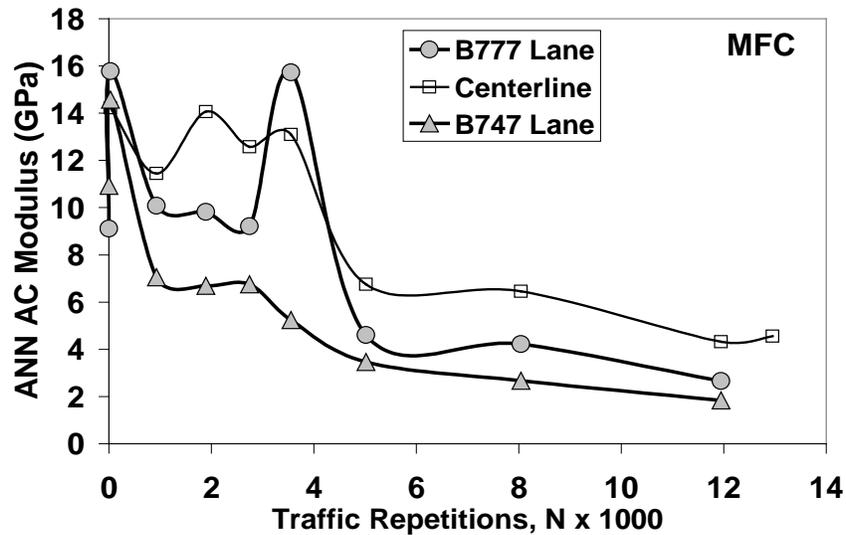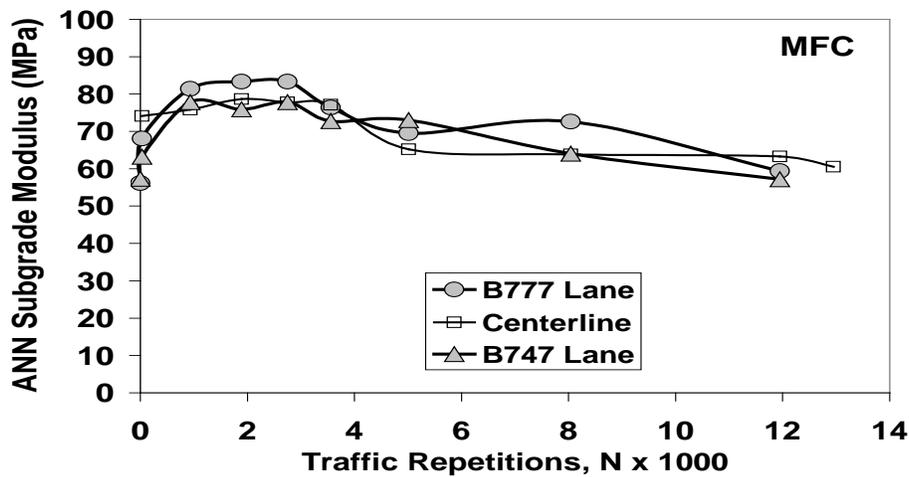

(a)
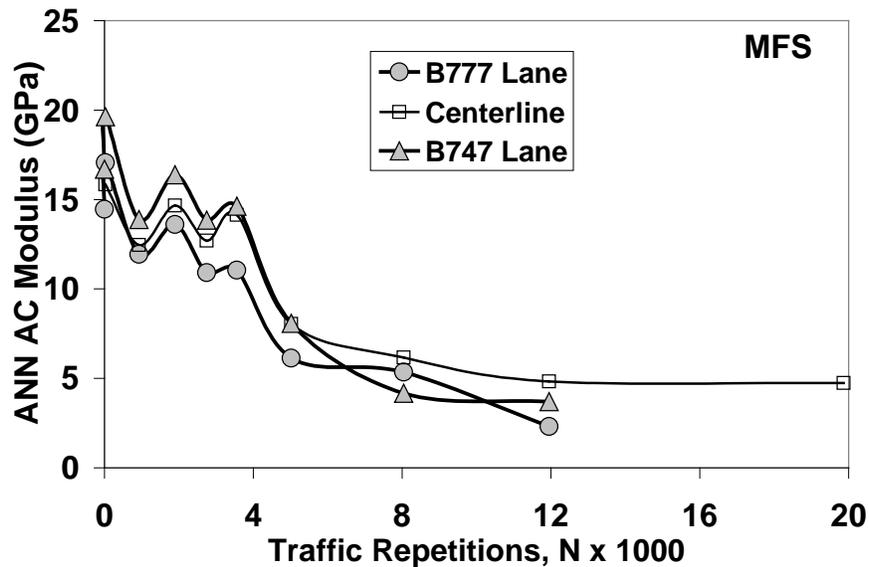
(b)

Figure 6. Changes in ANN backcalculated AC moduli during NAPTF traffic testing using 40-kN (9-kip) FWD test data: (a) MFC, (b) MFS.

Note that in the MFC test section, at around 3,000 traffic load repetitions, the E_{AC} for the untrafficked C/L is 12.5 GPa, while it is 9.2 GPa (74% of C/L value) for the B777 traffic lane and 6.7 GPa (54% of C/L value) for the B747 traffic lane. In the laboratory fatigue testing of AC specimens in constant strain mode, failure has been widely defined as 50% reduction in the initial stiffness (Ghuzlan 2001). Sharp and Johnson-Clarke (1997) suggest that a pavement may be considered to be failed when moduli are reduced by more than 50 percent.

The variations in ANN-based backcalculated non-linear stress-dependent subgrade moduli (E_{Ri}) with increasing number of traffic load repetitions are shown in figure 7 for MFC and MFS test sections. In the MFC test section, the E_{Ri} values varied within a range of 60 – 80 MPa during the course of traffic testing. In the MFS test section, the E_{Ri} values for both the traffic lanes and the C/L remained close to 85 MPa throughout the traffic testing.


(a)
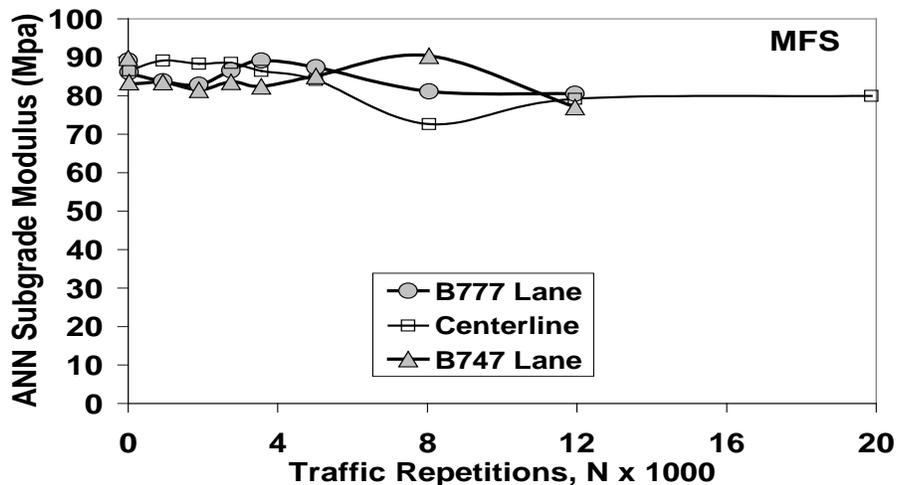
(b)

Figure 7. Changes in ANN backcalculated subgrade moduli during NAPTF traffic testing using 40-kN (9-kip) FWD test data: (a) MFC, (b) MFS.

The normalized 40-kN HWD deflection data was then used in BAKFAA to backcalculate the AC and subgrade layer moduli. The comparison between the ANN predicted moduli values and those obtained using the BAKFAA are shown in figure 8 for the full dataset. In general, the ANN AC moduli predictions are higher than BAKFAA values for the medium-strength subgrade flexible test section with the asphalt-stabilized base (MFS) whereas the opposite is true for the medium-strength subgrade flexible test section with the conventional aggregate base (MFC). In the case of subgrade moduli, the results are scattered and the BAKFAA backcalculated sugrade moduli are consistently higher than the ANN predicted moduli for the MFS test section.
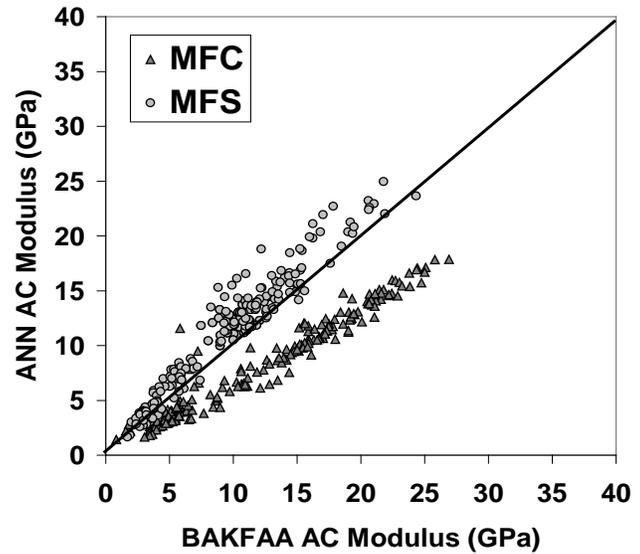
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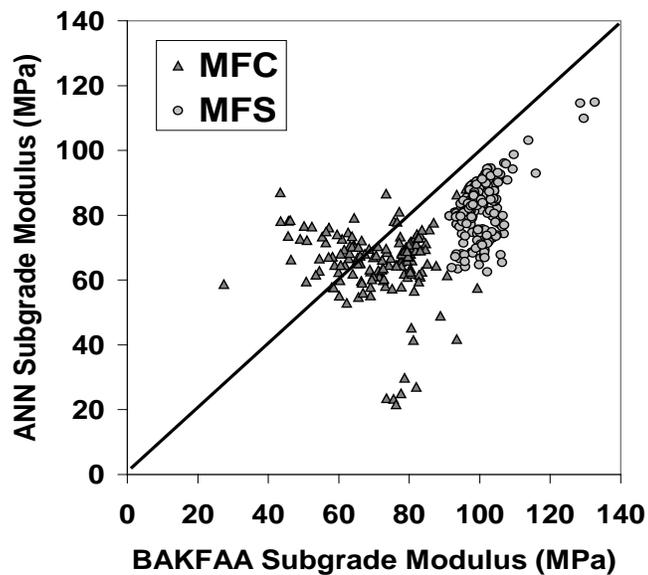
(b)

Figure 8. ANN moduli predictions compared with BAKFAA results: (a) AC moduli, (b) Subgrade moduli.

The differences in the moduli predictions between the two methods can be attributed to the different methodologies (elastic-layer program based versus finite element based) used in predicting the layer moduli.

The NAPTF rutting study results showed that, in general, the mean surface rut depth magnitudes between the B777 traffic lane and B747 traffic lane do not differ significantly throughout the trafficking (Gopalakrishnan and Thompson 2006). The post-traffic trench investigations revealed that both the subgrade and the subbase layers contributed to the total pavement rutting in both the MFC and MFS test sections (Hayhoe and Garg 2003).

8. Summary and conclusions

A study was undertaken to backcalculate the AC and subgrade moduli from NDT deflection data acquired at FAA's NAPTF during the full-scale traffic testing using an ANN based approach. Previous studies successfully demonstrated the ANN-based approach for backcalculating airport flexible pavement layer moduli from 160-kN (36,000-lb) HWD test data, specifically targeted towards the study of NAPTF flexible pavement sections. However, limited range of input properties were considered in developing the ANN training database.

In this study, validated ANN models trained over a comprehensive database of 28,500 datasets were employed for pavement layer moduli predictions. The ILLI-PAVE finite element synthetic solutions database, considering the non-linear, stress-dependent unbound granular layer and subgrade soil properties, were used for training the ANN. The ANN models successfully predicted the pavement layer moduli from the ILLI-PAVE finite element solutions. The best-performance ANN models were used to evaluate the NDT data acquired at the NAPTF during full-scale traffic testing with a dual-tandem Boeing 747 (B747) gear and dual-tridem Boeing 777 (B777) gear. The variations in pavement layer moduli properties during the course of traffic testing were studied using the ANN predictions and the results were compared with those obtained using an elastic layer program-based conventional backcalculation software.

The results indicate the potential of using 40-kN (9,000-lb) NDT test data for routine airport pavement structural evaluation as long as they generate sufficient deflections for reliable data acquisition. Thus, NDT force amplitudes at prototypical aircraft loading may not be necessary to evaluate airport pavements. The use of ANN-based structural analysis models can provide pavement engineers and designers with sophisticated finite element solutions, without the need for a high degree of expertise in the input and output of the problem. The rapid prediction ability of the ANN backcalculation models makes them promising evaluation tools for analyzing FWD deflection data in real-time for both project-specific and network-level FWD testing of airport pavements.

Acknowledgments

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