NATIONAL POOLED FUND STUDY
Problem Statement

IMPLEMENTING MECHANISTIC PERFORMANCE & LIFE CYCLE COST MODELING TOOLS FOR PRACTICAL PROBLEM SOLUTIONS

(Includes Suggested Pooled Fund Study Tasks)

September 1, 2004

OBJECTIVE

Methodologies and processes for use by transportation integrator organizations will be developed for designating key corridors and general use routes that serve trade, work commuting and tourism statewide. The study takes advantage of recent research developments in pavement performance and whole-life cost modeling so as to afford the use of these models in addressing high profile problem areas. The expectations of system performance in each corridor and on general use routes will be differentiated by customer need, intensity of usage, time of travel and other performance criteria. Emphasis is also placed on coordinating responsibilities between partners, customers and stakeholders. Included with these objectives is the conduct of training workshops so that at the conclusion of training the participants will have gained knowledge of the basic principles governing selected models and so that they will have mastered hands-on operation of that model inorder to use that model in solving practical problems. Also in included with these objectives is the evaluation of the NCHRP 1-37A pavement primary response and damage models.

BACKGROUND

The long term preservation of our existing highway infrastructure depends upon the nature of the traffic loads imposed, the influence of climate, the makeup of the materials that compose the pavement structure, construction practices and upon the policy actions of maintenance-rehabilitation-reconstruction (MRR). A large portion of our highway pavement infrastructure however reaches a failed condition prior to its design target life that is arbitrarily set between at 20 and 50 years, but some remain in service far beyond their expected load carrying design life only to become obsolete for other reasons. Many of these assets that do not reach their design target life, deteriorate to a condition where normal strengthening activity will not restore the asset to a condition that will provide an additional 20 or even 10 years of service with minimal M&R. Many times, complete reconstruction is necessary and then the newly reconstructed asset will again not meet design life expectations. In many instances, pavement modes of failure responsible for the premature deterioration of the asset are not known sufficiently to allow application of the appropriate tools for use in achieving the most effective design or M&R strategy. It is therefore essential that the appropriate tools and analysis procedures be used that will allow for the construction and preservation of a truly optimized highway infrastructure where pavement assets are at an optimum structural condition, provide maximum levels of serviceability and lifetimes, and at the same time, affect optimal MRR actions and minimal whole life costs.

Over the past several decades both the FHWA and state highway departments of transportation (DOT's) have invested heavily in the development of mechanistic performance prediction-lifecycle costing models and also in the collection and analysis of data associated with the performance of selected highway pavement test sections. Numerous mathematical models have been developed in order to address all sorts of pavement behavioral issues. For instance, NCHRP Project 1-37A provided both primary response and performance predictive models (rigid and flexible) intended for use in designing and analyzing pavements as a part of the 2002 Guide for the Design of New and Rehabilitated Pavement Structures. Also other agencies, including state DOT's, FHWA and universities nationwide have been working on developing mechanistic and mechanistic-empirical predictive models for use in addressing high focus issues e.g. NAFTA overloading or problems dealing with truck size and weight (TS&W) regulation. Two national Pooled Fund Studies (PFS) 2(203) and 2(205) with lead states Ohio and Texas respectively supported programs with these aspects in mind. Work in PFS 2(203) has provided a second-generation version of the VESYS mechanistic flexible pavement performance prediction model KB VESYS. This model will be linked to FHWA's life cycle costing model EAROMAR and the VSIM heavy vehicle dynamics model to form an integrated set of models called the KB Suite of Models. This same study further supported the development of FHWA's 2d Finite Element (FE) primary response program JSLAB and conducted evaluations on the EVERFEE 3-d FE model and selected parts of the NCHRP 1-37A flexible pavement PR model JULEA. Work in PFS 2(205) will provide a revised version of VESYS 5 specifically for pavement design purposes using a front end designed by the Texas A&M University. These models will be implemented along with other known models and the appropriate models will be selected for training and in developing strategies and procedures that address the objectives and scope of this PFS.

SCOPE

Delineation between new and exclusive truck routs, distribution hubs, intermediate truck/auto routs and exclusive light vehicle carriageways are foreseeable as effective means for meeting transportation needs well into the 2000's. Current arteries will need to be strengthened to meet such needs or to enable their existence to continue carrying today's traffic streams well into the future. Heavy vehicles, especially those designated as being overloaded vehicles must be classified with respect to the level of damage they impose and restrictions for their use must be equitably postulated. Heavy-duty truck routes that coincide more with the thickness designs of airfield pavements may be needed in order to carry trucks that could be as much as double the size of those compromising today's heavy vehicle fleets. Exclusive light vehicular traffic roads will necessitate more care in their design for environmental effects. Allocating user charges will certainly differ given such scenarios. The trend toward ownership of selected highways is inevitable and this certainly will require the use of sophisticated formulations and procedures that provide reliable estimates of the future wear out, performance and repair costs. This project is not to emphasize developing new models since much emphasis was placed on such developments over the past 20 years. Models that have been previously validated / calibrated will be selected for use in solving the assortment of practical problems dealing with pavement design, heavy vehicle damage etc. Appropriate training in the use of the models to solve specific problems is also to be emphasized and hands on operation is to be encouraged. In those instances where a selected concept or model needs to be enhanced, further verified, improved or "tweaked", then the study will take on this activity in preparation for the training and problem solving TASKS. In general the models that will be considered for implementation in this study should possess the following features:

- Have the capability to estimate those controlling or critical parameters (pavement performance, damage, response) and costs that are used by the State DOT in the decision making processes of MR&R, TS&W , pavement type selection, user charges or in identifying overloading restrictions on selected corridors.
- Easy access to a database (that is up gradable) that contains the major inputs needed to run the model for the corridor (s) being evaluated: environmental inputs in terms of temperatures and/or material properties; pavement geometry; vehicle configurations in terms of tire type, number of axles, axle type, axle spacing, vehicle weight and axle group weight; unit costs; road or corridor profile and road condition.
- Modular structure that will allow sub model improvement and/or upgrades

PROJECT ADMINISTRATION

The FHWA will serve as lead Agency and handle administrative duties for the project. Each participating entity may provide an individual to serve on the technical advisory committee that will provide direction to the project. A technical advisory committee (TAC) will be formed from the participants. The TAC will organize the specifics of the cooperative work tasks and oversee the accomplishment of these Tasks. Dr. Julian Bendana of the NY State DOT will serve as the Chair of the TAC. One person will be assigned from each state or as other wise directed by the TAC. The TAC will select the appropriate work tasks and help formulate work plans. They will also provide guidance and oversight regarding the execution of the research. Travel will be paid by the PFS. Dr. Bill Kenis is the FHWA contact.

ESTIMATED PROJECT DURATION: 48 months

BUDGET

The total project budget is estimated at $780,000. A partnership for funding this research is proposed between five state DOTs and the FHWA. The goals are:

NYSDOT: 50k per year for 4 years	$200,000
4 other states DOTs @ $25k each per year for 4 years	$400,000
Total State DOTs	$600,000
FHWA LIKE KIND CONTRIBUTION	$180,000
Total Estimated Budget (min)	**$780,000**

RECOMMENDED PROJECT TASKS

TASK A Training ($150,000)

OBJECTIVE

Select validated models and conduct training workshops so that at the conclusion of training the participants will have gained knowledge of the basic principles governing a selected model's formulation and will have mastered hands-on operation of that model in solving practical problems.

BACKGROUND

Major emphasis of the TPI research program and the Pooled Fund Studies 2(203) and 2(205) was the development/linking of mechanistic-empirical performance predictive model sets for flexible and rigid pavements. It should be stated that any mechanistic or empirical pavement predictive model must be verified and calibrated for different sets of environmental, material, and traffic conditions. Only then should modifications and improvements to the model be made and applications for the design process implemented. In this context, verification is defined herein as the process of confirming the correctness of the model. Calibration is simply a way of fine-tuning a model to achieve more accurate predictions under local conditions, and should not be considered as a substitute for the process of verification. In practice however the conduct of validations and calibrations go hand in hand:

- VSIM (stands for Vehicle SIMulation) is a mechanistic vehicle vertical dynamics time domain simulation model that supports an arbitrary large number of vehicle body tractor or trailer and axle configurations. Governing equations account for the heave, pitch and roll degrees of freedom. It is capable modeling single, tandem, tridem and walking beam non-linear leaf springs and single and tandem air bag suspensions. The leaf spring model makes use of the Fancher formulation for non-linear hysteresis behavior (rather than using the spring-Coulomb in parallel model of Phase 4). The Fancher model was developed by curve fitting force deflection data obtained from experimental measurements. VSIM also includes non-linearity such as wheel hop and shock absorbers, viscous damping and hysteresis rocker, as well as three different tire models: point contact, fixed footprint, and adaptive footprint models. The VSIM model is comprehensive enough to simulate all possible configurations of vehicles on the road and to allow for easy modification and user input subroutines to accommodate futuristic vehicle geometrics. VSIM has been validated by comparing predicted tire forces with (1) tire force measurements obtained from field tests in which instrumented vehicles run on a test track facility at different speeds and over different pavement profiles created by in-place pre-fabricated bumps, and (2) shaker table tests to simulate truck wheel force output by placing an instrumented truck on a shaker table under input from computer controlled actuators that simulate real road surface profiles. Both predicted and measured wheel force time histories were used to calculate force power spectral densities (PSDs) for selected truck test conditions. Over several hundred computer plots were generated in the conduct of the calibration process to calculate a normalized tire force, PSD's etc. for the test conditions identified using the calibrated parameters. We concluded that the final vehicle parameters attained are reasonable estimates of what the parameters should be. Vehicles normally vibrate in 3 major modes as frequency increases (bounce, pitch, and wheel hop). The conduct of shaker table harmonic sweep tests to identify these different resonant frequencies will enable quick and accurate back calculation of the different vehicle parameters. The PSD function consists of distinct peaks corresponding to the resonant modes, and it is much easier to detect which parameter needs to be altered for a given mode.

- EAROMAR (Economic Analysis of Roadway Occupancy for Maintenance And Rehabilitation) is a complete life cycle cost (LCC) analysis model that estimates a wide variety of both rigid and flexible pavement damage and performance outcomes for different environmental conditions and highway traffic scenarios; it applies the necessary maintenance and rehabilitation (M&R) strategy and it calculates the total of agency and user costs associated with a given project level scenario. The upgraded version of EAROMAR will allow users to input their own primary response and damage models or measurements, in addition to the empirical relationships inside the program.
- VESYS is a flexible pavement structural subsystem model that consists of three mechanistic model sets that are uniquely integrated: a primary response model set, a damage model set, and a performance model set. Each model set depends on separate input and on prescribed interrelationships between the sub-models e.g. the primary response model calculates stresses, strains or deflections and passes these on to the damage models. Based on the values of the damage components, the program calculates the road serviceability after a given time period. Also, since the factors which affect real world damage and performance of a pavement system are known to vary in a stochastic fashion, therefore, all of the VESYS structural subsystems were developed to incorporate options for probabilistic solutions. In this sense, inputs to the component model sets are described as statistical distributions instead of single-valued estimates, and outputs are presented in terms of means and variances. Currently there are three different versions ready for implementation: VESYS 5W, VESYS 5T and KB VESYS. VESYS 5W and 5T were developed by FHWA and enhanced under PFS 2(205). VESYS 5T is the latest version and represents the needs of the PFS participants. The KB VESYS model was developed by FHWA and enhanced under PFS 2(203). KB VESYS houses the same drive engine as the other versions however it is more comprehensive. It was developed to be linked with VSIM and EAROMAR as part of the KB suite of models. The KB VESYS version has not been subjected to user scrutiny for ease of use, as have the other versions of VESYS. The VESYS models have been validated and calibrated thoroughly by using accelerated loading and other field test data. The primary response model was validated and calibrated using test data collected form FHWA's test road and the OHIO/SHRP test road. The performance models were validated and calibrated using data collected from accelerated loading tests conducted at FHWA, Texas, Louisiana and CAPTIF as well as with AASHO road test performance data.
- JSLAB 2004 descriptions and validations are described elsewhere in this document.
- KB SUITE OF MODELS The overall goal is the linkage of the above listed model sets to form an advanced integrated suite of models that can not only provide pavement performance prediction with consideration of truck dynamic load and environmental condition effects, but also account for the life cycle costing of the highway infrastructure. This research is one of the first attempts to bring together the essential components of both theoretical and practical concepts to form an integrated framework applicable in addressing issues dealing with the preservation of the nation's highway pavement infrastructure

The NCHRP 137A rigid and flexible pavement primary response and performance models described elsewhere in this document will also be available for hands on training purposes.

<u>SCOPE</u>:

Mechanistic modeling tools have been available for decades. Many of these tools have been verified over and over but there has been a general reluctance by the practicing engineer in putting these models to use. A better understanding of the basis of the model formulations, hands on implementation of the software itself and reasonable assurance of the validity of a given model will certainly go a long way in furthering the use of these tools. Normally tasks involving training applications are scheduled to occur at the end of a research project and then funding becomes limited. Therefore since the PFSs 2(203) and 2(205) have either made use of or furthered the development of a number of mechanistic and M-E modeling tools, and since these tools are sufficiently validated and many are sufficiently calibrated, then it is feasible that these models be made available for use by the participants of this pooled fund study for their use in attempting to apply the models in solving problems of their choice. User manuals and documentation packages will be provided for any model(s) selected for training. Detailed explanation of model inputs will be provided along with sample input files that include most commands comprising the software.

TASK B JSLAB 2005 ($75,000)

OBJECTIVE

Upgrade J-SALB 2004

BACKGROUND

Improvements to JSLAB 92 were completed under the direction of the 2(203) Pooled Fund Study team through an FHWA contract with Galaxy Inc. that resulted first in JSLAB 2002 and then JSLAB 2004. The effort that resulted in JSLAB 2002 accomplished the following:

- Programmed options for six different subgrade types: Spring, Winkler, Elastic, Two Parameter, Three Parameter and ZSS
- Developed a user friendly graphical interface consisting of pre and post processors
- Tested the software theoretically and by comparisons with BISAR, the FAA's H51 and JSLAB 92 and with pavement test data from the Ohio Test Road.
- Provided a users manual

The PFS review team determined, that even with the GUI provided, that the program's required ability/flexibility to allow users to investigate the many complex cases (varied sizes of finite elements, un-equal slab thickness and material properties, different foundation characteristics, and arbitrary output locations, etc.) required a series of input data that were not needed by many users. Although the JSLAB program must be able to handle such complicated cases, it was determined that a "express method" (less detailed input requirement) option be implemented to accommodate the more frequent of user needs. The effort that resulted in JSLAB 2004 accomplished the following:

- Installed an axel configuration library that includes single, dual, and super single tires and tandem, triple and quad axles configurations
- Added capability to allow the user to easily change the loading areas, axle spacing for multiple axles, and to move the axle groups to any position on the slabs.
- Added the capability to directly calculate the response time history at specified locations within the pavement under a moving axle and/or vehicle in order to simulate responses in the field. The program internally moves the load a suitable length step, and calculates the response at each step. Appropriate plots are made.
- Provided a "Express" interface (option) that generate input data for most common needs including the pavement mesh plan. The "Express" option is run under the Jslab main program for response distributions without modification but it can be modified, using the original interface, to investigate more complicated cases.

In the earliest version of JSLAB, FHWA/RD-86/041, page 27, it is stated that the curling analysis was done for a single slab only. In another FHWA report (1992), May Dong found an error in the curling formula and immediately made appropriate corrections and results verified by theoretical and numerical comparisons. The model also handles multiple-slab curling for response distribution; however, no verification has been seriously attempted for proving the accuracy of multiple slab curling.

<u>SCOPE</u>

- Modify the current ZSS foundation model to improve the accuracy of the slab response when a load is applied at the edge or corner of a slab. JSLAB 2004 only considers the contribution of a portion of the elastic semi-infinitive space under the slab.
- Theoretical and numerical verification of the multiple-slab curling algorithms.
- Expand the capability to predict the response time history of a pavement with three curled slabs in each direction. The current analysis is for a pavement with multiple flat slabs in each direction. The program will be modified to automatically eliminate the effects of tires outside of the pavement area being analyzed. If the slab number needs to be increased to six OR seven, the program engine would need to be REPLACED.
- REPLACE the current engine of the JSLAB 2004 program (numerical solver) with a more effective one and modify existing subroutines to fit the needs of the new engine: response time history of a curled pavement with multiple slabs, increase the number of slabs for handling very long vehicles, back-calculating the pavement for situ material properties, predict the response of slab under nonlinear temperature and/or moisture gradient (needs to install three dimensional elements).
- Add the capability to handle non- uniform support (under one slab or several slabs) to mainly account for utilities, such as catch basins and man holes, that are typical cases for urban PCC pavements.
- Upgrade JSLAB 2004 to present output in graphical color form so that contours indicate the magnitude of the responses. Tables should be included that further summarize pertinent critical responses.

TASK C Practical Problem Solution Techniques ($150,000)

<u>OBJECTIVE</u>

Implement validated models to obtain practical problem solutions commensurate with the SCOPE of this Pooled Fund Study.

<u>BACKGROUND</u>

A Truck Size and Weight study using VESYS 5 (flexible pavements) was conducted at the request of the of the US Congress to examine key influencing factors such as tire type (dual versus super single), tire pressure, differential tire pressure, suspension type, spatial repeatability, rolling tire effects, etc. Recommendations were provided to the Congress as technical basis for establishing TS&W policy. The EAROMAR model has also been used to study problems that require calculations of both user and agency costs over a prescribed life cycles: pavement type selection, warrants for premium and long lasting pavements, cost apportionment scenarios, optimal strategies for MRR, establishing trigger values for MRR etc. A new version of VESYS called VESYS 5T was developed as part of PFS 2(205) and it will be made available for use in this task. Also the new KB SUITE of models that considers vehicle dynamics, pavement response and life cycle costs (developed in PFS 2(203)) will be made available for this task. A preliminary attempt to apply VESYS in attacking NAFTA type problems was completed for PFS 2(205) using VESYS 5. This effort proposed a simplified methodology for identifying the damaging impact of heavy NAFTA type trucks that is presented in terms of a vehicle load equivalence function, VLEF, and a vehicle payload equivalence function VPEF. To arrive at these damage indicators the VESYS 5 model was implemented, for a standard vehicle (loaded and empty) and for different vehicle types (loaded and empty) to calculate the number of vehicle or axle group repetitions to research a prescribed damage / performance threshold.

The KB SUITE of models (VSIM, EAROMAR and KB VESYS) has been structured to meet the requiremts set forth in the overall scope of this study. This model set will be made available for problem solving purposes for this Task. The Vesys 5T model enhanced by TA&M will also be made available. Currently PFS 2(205) is developing a 3 d finite element model at the Un of Texas El Paso to meet the requirements set forth in the overall scope and this model could also be made available for training and problem solving in this Task. Further, the NCHRP 137A rigid and flexible pavement analysis/design models that are being evaluated as part of this study may also be used for problem solving purposes in this Task.

SCOPE

Methodologies and processes for use by transportation integrator organizations will be developed for designating key corridors and general use routes that serve trade, work commuting and tourism statewide. The study takes advantage of recent research developments in pavement performance-whole-life cost modeling so as to afford the use of these models in addressing high profile problem areas pertaining to such key corridors and/or general use routes. Emphasis is also placed on coordinating responsibilities between partners, customers and stakeholders. The expectations of system performance in each corridor and on general use routes will be differentiated by customer need, intensity of usage, time of travel and other performance criteria. The conduct of model simulations to investigate the impacts of heavy trucks traffic (especially Canadian and Mexican trucks on US highways) will be emphasized. The TAC panel will have the choice of selecting those models that offer the best opportunity for solving such problems.

TASK D Viscoelastic and Viscoplastic AC Test Authentications ($25,000)

OBJECTIVE

Determine the authenticity of (1) claims for the need for both viscoplastic and viscoelastic material characterizations in the practical arena and (2) claims that a new device developed at FHWA allow testing pavement cores to provide responses similarly as larger 4 inch diameter by 8 inch high specimens for resilient , plastic and viscoelastic properties.

BACKGROUND:

The study of the rheologic behavior of materials normally deals with those materials' properties that depend on the time of loading and where the states of stress do not produce plastic flow, i.e. those materials exhibiting combinations of elastic, viscous or viscoelastic behaviors. The study of the theory of plasticity, on the other hand deals with those materials whose properties depend primarily on the path of loading and where the duration of loading is sufficiently short (but preserving a quasi static process) so as not to allow the onset of creep or relaxation that is associated with viscoelastic materials. It is known however that in most practical problems, that the behavior of real materials is governed by rheologic as well as plastic behaviors. We therefore classify such materials as viscoplastic materials or simply as rate sensitive plastic materials. AC is a viscoelastic material under medium loading rates but at high loading rates and dynamic actions the material may well behave in a viscoplastic manner. The complex behaviors under both medium and high loading rates must therefore be accounted for through energy dissipation type characterizations.

The FHWA has developed a new device to be used with cores from pavements less than 8 inches thick so that test results will be more in line with similar tests conducted on 8 inch tall specimens.

SCOPE

Determine the influence of vehicle speed to accommodate the onset of viscoplastic behavior in elastic and viscoelastic materials. Conduct series of laboratory tests to validate viscoplasticity concepts previously developed (Schapery-Park-Kim , Perzyna and Sharma-Kenis). Upon completion, the validated model(s) may be used in a practical sense to estimate the development of damage under high speed conditions for comparison with that predicted using common viscoelastic / elastic / plastic methods developed for use in VESYS and NCHRP 137A for moderate traffic speeds. Creep, relaxation and constant strain rate tests will be conducted on Hot Weather Shear test section cores recently taken from the Hot Weather Shear test sections at the OHIO/SHRP test road. Calculated stresses strains and permanent deformations (using available models will be compared with measured values. If the theory of viscoplasticity and hysterisis energy concepts do not explain the measured phenomena, it will be so stated.

Since the test pavement is composed of both 4 inch and 8 inch pavement sections, then comparison of results using the new FHWA device and shorter samples with the results from the the 8 inch cores will determine the authenticity of that device.

TASK E AASHO Test Road Flexible Pavement Data Base ($20,000)

OBJECTIVE

Enhance the plot routines of the TPI-AASHO ROAD TEST flexible pavement database to allow plotting any combination of the performance measures with time and/or repetitions.

BACKGROUND

The development of the TPI-AASHO flexible pavement database was initiated over 20 years ago. Data from hard copy data sheets was painstakingly assembled onto data tapes for use with the IBM 360 computer. The LENDIS CORP painstakingly again reconstructed (whilst simultaneously encountering and correcting numerous errors) these tapes to evolve software for personnel computers. The resulting program was used by FHWA on PFS 2(205) in calibrating VESYS 5. In order to make these data trends more easily assessable to the participants of PFSs 2(203) and 2(205), the LENDIS Corp. developed a user friendly front end (GUI) (this development will be included in the final reports to the two PFSs). In developing the software, provisions were made to include an enhanced graphical interface that would allow the user to conveniently view the pavement damage/performance trends (trends are ideally suited for mechanistic model validation).

SCOPE

This database has been in development off and on for 25 years (costing over $75,000). It has recently been used to calibrate/validate the VESYS 5 flexible pavement performance models however not in a very friendly manner. The new Windows version has the capability of assessing any of the data but lacks a universal plotting interface. Work here only involves programming to complete a graphical interface to insure flexibility.

TASK F - Second Generation Design Models ($150,000)

OBJECTIVE

Provide improved an updated mechanistic predictive formulation perceived for the next generation of design/performance models.

BACKGROUND:

The current NCHRP 137A design models and VESYS incorporate mechanistic-empirical damage type models that do not account for the dynamic action of the array of heavy vehicles imposed, the progressive accumulation of crack growth patterns or of the viscoplastic (if authenticated) response of the AC layers. The models do not account for the internal progression of damage due both to the dynamic actions of heavy vehicles (with coupled climatic effects) or to damage due solely to environmental causes. The FHWA through VOLPE has developed a comprehensive fracture mechanics model that calculates the progression of cracking in either flexible or rigid pavements. It was developed to replace the Minors Law model currently in KB VESYS and the KB suite of models enhanced under PFS 2(203).

SCOPE

The scope of the effort involves the development of software for both AC and concrete pavements that integrates a truly mechanistic fracture mechanics (FM) crack propagation model and a truly mechanistic incremental permanent deformation model within the broad framework that is capable of simulating a variety of pavement types, environments, materials properties, vehicle types, tire types, wander, axle groups etc. The integrated model must also be able to address the combined interactions of cracking, water infiltration, and rutting and roughness and the costs associated with the internal progression of damage because of these interactions. The overall model set should further be able to address the effects of pavement construction variability and its effect on pavement life and smoothness and have the capability to be linked with Life Cycle costing models (agency costs, user costs, and vehicle operating costs) and vehicle dynamic effects models.

TASK G1 FHWA Like Kind Contribution: NCHRP 1-37A Rigid Pavement Damage Model Validation ($80,000 funded directly by FHWA)

OBJECTIVE

Evaluate the NCHRP 137A rigid pavement performance models as they relate to the set of rigid pavement design procedures proposed for use by AASHTO.

BACKGROUND

The NCHRP 1-37A has completed development of a set of rigid pavement mechanistic-empirical predictive models and associated design procedures. These models/procedures however have had limited peer review and no independent evaluation of either the technical or operational aspects. The guide includes selected models/procedures for four different rigid pavement types: jointed plain concrete pavement (JPCP), continuously reinforced concrete pavement (CRCP), rehabilitation of JPCP (RJPCP) and rehabilitation of CRCP (RCRCP) (rehabilitation of Asphalt Concrete pavement is also included in the GUIDE however it will not be covered in this contract). The rigid pavement design procedures are based on combinations of four different performance model types: fatigue cracking (JPCP) , faulting (JPCP), punch-outs (CRCP) and roughness or IRI (JPCP and CRCP). Cracking, faulting and punch out type models are normally considered to be true DAMAGE models however the word "performance" is normally reserved to refer to functional aspects e.g. the life of the pavement in terms of road roughness, profile statistics, deduct points, slope variance, IRI etc. For simplicity, we refer to the whole set of models either as damage or performance models without distinction.

A sensitivity analysis was conducted on the JPCP model as part of a Masters Degree thesis at the University of Arkansas. The purpose was to evaluate, by means of a quasi-sensitivity dual level analysis, the inputs for the JPCP design in order to obtain a better understanding of the degree to which those inputs have an impact on the outputs or on a specific damage model. The study examined only the sensitivity of the inputs pertaining to the concrete slab itself. The procedure allows one to select from three different LEVELS of input requirements depending on an assigned number of default values. The least number of inputs is assigned to LEVEL 3. It is suspected that the procedure requires over 100 inputs (current 1993 guide requires only 11 inputs) for a LEVEL 1 analysis. The University of Arkansas also found that of the 29 inputs associated with the PCC slab only (except for edge support, a drainage path length input and an erodability input) that only eleven were seen to effect cracking and seven to effect faulting significantly. Eighteen of the variables had an insignificant effect on faulting and cracking demonstrating that almost 50% of the required inputs were of an insignificant nature in the design process. It was also found that there were instances where the software or models had errors.

The cracking model is based on field sections that were part of the Long Term Pavement Performance (LTPP) study as well as from the Federal Highway Administration's study Performance of Concrete Pavements. The 2002 Guide states that there are approximately 1 million cases that must be analyzed each Transfer Efficiency (LTE). There are a number of different types of LTEs defined e.g. dowel, joint, base, and aggregate and year over the design life of the pavement.

The faulting model is based on the accumulation of an incremental amount of faulting for a given season. The amount occurring in any one season is a complex compilation of models. The Guide defines a differential deformation energy term and a differential corner deflection term that is the difference between deflections on the loaded and unloaded side of a joint. The corner deflections are further defined in terms of Load these are summed to obtain a total LTE.. The user inputs individual LTEs to the program and the software produces individual (or total) DCDs that are then used to calculate the DEs. The equations used to calculate the DCDs were developed using the ISLAB 2000 model where LTE conditions prescribe the boundary conditions for a given problem. There are also a few other equations that account for loss of shear capacity etc. The Guide states that the faulting equations contain 34 constants some of which also contain other variables e.g. FREEZE index.

The smoothness model is to represent IRI at any particular time. It is dependent upon the cracking and faulting models. A site factor is given in terms of AGE, FREEZE INDEX, and % material passing the 200 sieve. Spalling is represented by a rather complex equation in terms of age and a SCALING FACTOR that is further given in terms of a number of assorted variables.

SCOPE

The contractor shall obtain literature, software and executables necessary for evaluating the NCHRP 137A's rigid pavement performance models and their application for use as a new mechanistic – empirical design procedure. Work involves analyses that will determine the mathematical viability of the models and the sensitivity of the independent variables in terms of a given model's ability to estimate in-service pavement damage and performance. The work shall develop a viable plan of study that will include a workable sensitivity test matrix that includes most of the important input parameters necessary for operating the individual models. The contractor shall thoroughly test the existing concepts and software and report on its performance relative to AASHTO's design philosophy applicable to state department of Transportations, demonstrating the extent to which the models and procedures meet accepted levels in the design process. At the conclusion of the contract, the contractor shall install the software on-site at TFHRC and in at least one State DOT, and provide accompanying documentation, pros, cons, limitations and ranges of usable variables, recommendations for needed program changes and on-site demonstration of the documentation developed

TASK G2 FHWA Like Kind Contribution: NCHRP 1-37A Rigid Pavement Primary Response Model Validation ($100,000 funded directly by FHWA)

OBJECTIVE

Validate and make/suggest improvements to the NCHRP 137A rigid pavement design models with major emphasis on the accuracy and operational aspects of the Primary Response models as these are integral with the overall 1-37A Mechanistic-Empirical (M-E) proposed design procedure.

BACKGROUND

Most of the information pertaining to the NCHRP rigid pavement PR models is available in Appendix QQ Evaluation criteria for the selection of theses was based upon the ability of a model to predict the correct answer and it's ease of application in a practical design environment. The 3D FE ABAQUS software was thought to be the most promising tool among general-purpose finite element packages. The models ILSL2 and ISLAB2000 were selected among the plate theory-based programs and EVERFE was selected as a 3D-pavement program specifically developed for rigid pavement analysis. ABAQUS incorporates implicit (ABAQUS/STANDARD) and explicit (ABAQUS/EXPLICIT) dynamic solvers to allow analysis of a wide range of linear and nonlinear applications. ILSL2 is the latest public domain revision of the finite element program ILLI-SLAB, whereas ISLAB2000 is a proprietary revision of ILSL2, developed by ERES Consultants in cooperation with several different universities. These two programs are generally referred to as ILLI-SLAB in the design guide. The model incorporates six subgrade models, however only the Winkler model is recommended for the 2002 Design Guide.

The "k" value valid for the dense liquid foundation is to only represent the granular base and subgrade and foundation effects, and therefore. A bound base layer ideally should be considered as an improvement to the structural capacity of the slab and should be modeled with it's thickness, elastic modulus and degree of friction. Most finite element programs for PCC pavements conduct analysis of two-slab systems by converting these systems to a structurally equivalent single-layer system. Because the two pavement layers are not actually modeled as two separate layers, the programs cannot analyze the independent actions of the two layers. Until recently, the separation between the slab and the base could only be modeled using 3D finite element programs. ILSL2 incorporates an approach, developed by Totsky, to analyze this problem wherein ing on subgrade is modeled as a series of springs and plates. The plate elements model the bending, whereas the springs accommodate the direct compression occurring in such a system. The curling problem in the Totsky model is solved iteratively. The analysis begins with all of the interface springs in compression (compression due to the self-weight of the slab). The pavement layers are then allowed to curl. If any of the springs are in tension at the end of the first iteration, those springs are removed and the system reanalyzed. For CRC pavements an equivalent structure concept is developed based on the assumption that top surface stresses in two rigid pavements are directly related if certain conditions involving the radius of relative stiffness, void width, crack spacing, Korenev's non-dimensional temperature gradient etc. are satisfied. From these assumptions, a simplified equation is developed that allows one to calculate the stress in a two layered slab system from the stress existing in a single slab (see equation 4.19 of Appendix QQ).

The "k" value, that represents granular base, subgrade and embankment effects is calculated (rather than input) using, in part, layer theory and a single circular load at the surface of the slab that rests on a semi-infinite half space. Because the subgrade may be assumed as being stress dependent non-linear, an effective subgrade elastic modulus is calculated from iterations between "layer theory" slab surface deflections and a laboratory determined non-linear subgrade material characterization function. The k value is then obtained from the definition of the "radius of relative stiffness" for a slab on the dense liquid foundation.

The four-step approach of Korenev and Chernigovskaya was implemented into ILSL2 to account for the non-linearity of the temperature distribution through a concrete slab. The temperature distribution throughout the slab thickness is split into three components, one causing slab expansion or contraction, another causing curling (i.e., slab bending), and a third tending to cause distortion of the cross-section, thereby giving rise to self-equilibrating stresses resisting this distortion.

Appendix QQ of the NCHRP 1-37A Guide documentation, states that the computer program ISLAB2000 was selected for use in the design guide rather than using 3D FE programs primarily because of computational time constraints. Nevertheless, the NCHRP contractors decided to implement artificial neural networks (NN) in lieu of using the 2D ISLAB2000 model. They state that previous models used regressions to calculate the stresses (normally for mid slab edge loading conditions, the maximum bending stress is the critical one that is used account for bottom-up fatigue cracking) but that these regression equations were are not suitable because of their inability to analyze the effect of tandem and tridem axle configurations and that to adapt these models to handle multiple axles is a complex and time-consuming process. Therefore, they used ISLAB2000 to get new "regressions" from NN software packages to predict responses for a variety of combinations of design and loading parameters. Limitations were single slab size and an inability to analyze the effect of the base layer. An equivalency concept is introduced to reduce the number of independent input variables required for training the NN.

The structural model used for the prediction of CRCP responses incorporates Neural Network algorithms to predict critical top-of-slab tensile bending stresses in CRCP that lead to punchouts. The Equivalent CRCP Structural concept is also used.

A preliminary effort to validate the ISLAB 2000 model was undertaken in PFS 2(203) and it was determined that some flaws may exist in the code. These findings are being further checked in TASK G2 and they will be reported at the first TAC meeting.

SCOPE

Both theoretical accuracy and practical trend validations of the appropriate models (finite element, layer theory and neural network algorithms) will determine the accuracy of the primary response (PR) models, as they are integral with the calculations of rigid pavement damage/performance. Theoretical accuracy validations will involve simulations, sensitivity trials and comparisons (with other validated models) of calculated slab stress, strain, deflection and curling response at an array of coordinate points over a range of different combinations of traffic, environments, joint spacing, dowel configurations, base courses etc. PR practical trend validations will compare calculated PR traces with measured PR traces for moving loads at different speeds and for different temperature gradients for presumed curled conditions. This analysis will be conducted for both jointed plain concrete pavements (JPCP) and for continuously reinforced concrete pavements (CRCP).

TASK G3 FHWA Like Kind Contributions: NCHRP 1-37A Preliminary Flexible Pavement Model Validation (Initially $20,000 is applied and upwards from $150,000 may be made available pending the out come of FHWA's FY 2005 budget appropriations). The preliminary validation study will be made available to the participants at the first TAC meeting.

OBJECTIVE

To validate and suggest/make improvements to the NCHRP 1-37A flexible pavement (a) primary response models JULEA and the finite FEM option and (b) damage and performance model algorithms so that they will be used with a known degree of reliability and accuracy as an integral part of the overall design framework. This Task will include summarizing and organizing results from PFSs 2(203) and 2(205) as well as from other studies.

BACKGROUND

Current methodologies and technologies used for the design of flexible pavements are predominately "Failure Based" methodologies that consider only the traffic that has caused the pavement to reach a predetermined level of service/deteriorated state. No consideration is given to the initial structural integrity of the pavement neither in terms of stresses, strains and deflections nor to the systems integrity over its lifetime. The methodology does not consider pavement elastic or viscoelastic material characterization, construction quality, or the very complex nature of the vehicle itself. No consideration is given to tandem axle spread, load-sharing capabilities, axle type (air or spring) nor tire aspects. Therefore, the FHWA, and states have allocated considerable funding for the development of the NCHRP 137A and KB VESYs structural subsystems for mechanistic pavement response and performance modeling in order to account for the combined effects of traffic load and material property changes over time.

SCOPE

Both theoretical accuracy validations and practical validations are required. Theoretical PR validations will involve simulations, sensitivity trials and comparisons of calculated PR over a range of space points. Calculated values from JULEA and the 1-37A FE (for unbound materials) models will be compared with other proven closed form type models e.g. BISAR and KB VESYS. These validations will determine the degree of reasonableness of the stress strain and deflection estimates relative to magnitudes, lag times, differences between peaks and valleys and relationships to vehicle speed and temperature. Practical validations will compare calculated primary responses with in-situ measured PR response traces in the pavement as loads roll across the surface of the pavement at different speeds and for different temperatures. Measured response traces that include layer deflections from single and tandem axles that incite quasi-static response are required. The use of most dynamic type loadings qualify in this regard e.g. the DIVINE/CAPTIF data and the DIVINE/TFHRC data obtained at various vehicle speeds and known degrees of pavement roughness (profile). Only that data known to be immediately available and completely documented will be used e.g. the PR data from the Ohio LTPP test road and the Ohio/ SHRP Hot Weather Shear (HWS) test sections. During these tests, strain gages and LVDTs were strategically placed in two asphalt concrete sections of different thickness. What makes these tests unique is that vertical and horizontal gages were placed in the pavement allowing the computation of vertical shear strains that were not previously available from any other experimental road test sections. All data except the DIVINE data should be statistically quantified before it is used in the PR calibrations. FWD surface deflections may be used but only in conjunction with moving load data.

Theoretical validations will involve simulations, sensitivity trials and comparisons of calculated damage and performance over a range of different combinations of traffic, environment and layer material properties. Calculated damage will also be compared with calculated values using other validated and calibrated damage /performance models e.g. the VESYS rutting, cracking, roughness and serviceability sub models. Other known damage prediction models will be sought for comparisons, as needed. These validations will determine the degree of reasonableness of the models and allow for immediate corrections to be made to hasten state implementation. Practical validations may compare predicted damage estimates with measured damage from selected test sections from the AASHO Road Test, selected accelerated load test data, LTPP performance data or data from the OHIO/SHRP test road.