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16. Abstract

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The objective of this research was to develop an overlay design method/procedure that is used for a structural overlay thickness design of flexible pavement in Louisiana based upon (1) in-situ pavement conditions and (2) non destructive test (NDT) methods, specifically the falling weight deflectometer (FWD) and/or Dynaflect.

Fifteen overlay rehabilitation projects were selected for this study. These projects were strategically located throughout Louisiana with different traffic levels. At each selected project, NDT deflection tests including the falling weight deflectometer (FWD) and Dynaflect were performed at a 0.1-mile interval. For some of the selected projects, detailed condition survey data including cracking, rut depth, International Roughness Index (IRI), mid-depth temperature, and pavement thickness was also collected. Six NDT-based overlay design methods were selected and used in the overlay thickness design analysis. Results indicated that the 1993 AASHTO NDT procedure generally over estimated the effective structural number for the existing asphalt pavements in Louisiana, which would result in an under-designed overlay thickness. On the other hand, other NDT methods (i.e., ROADHOG, Asphalt Institute MS-17, Louisiana 1980 Deflection method, ELMOD5, and EVERPAVE) were found inapplicable to the Louisiana pavement conditions because all those methods rely on locally calibrated design parameters. Since further calibration of those NDT methods requires additional testing resources and is also considered very time-consuming, a modified FWD deflection based overlay thickness design method was proposed in this study. This method, based upon the Louisiana Pavement Evaluation Chart (a relation between Dynaflect deflections and the structural number of existing pavements) and in-situ subgrade modulus, is deemed able to directly represent Louisiana's pavement condition. The cost/benefit analysis revealed that, as compared to the current LADOTD component analysis method, the proposed NDT-based overlay design method would potentially save millions of dollars in the flexible pavement rehabilitation in Louisiana. Therefore, before full implementation of the new Mechanistic-Empirical (M-E) pavement design method, the proposed NDT-based overlay design method is recommended for implementation by LADOTD.

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Mechanistic Flexible Pavement Overlay Design Program

by

Zhong Wu, Ph.D., P.E.
Kevin Gaspard, P.E.

Louisiana Transportation Research Center
4101 Gourrier Avenue
Baton Rouge, LA 70808

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IMPLEMENTATION STATEMENT

A structural overlay thickness design procedure based on non-destructive surface deflection testing (i.e., FWD) will be implemented as a result of this research study. One primary advantage of the developed design procedure over the current LADOTD overlay design method lies in the elimination of reliance on human judgment in the estimation of an existing pavement structural number and subgrade modulus, and thus, the overlay thickness design can be based on in-situ pavement conditions. This procedure will be used routinely for the thickness design of structural asphalt concrete overlays for flexible pavements in Louisiana. Since this procedure uses a similar set of design inputs [e.g., design reliability and traffic loading in term of equivalent single axel loading (ESAL)] as the current LADOTD overlay design method, implementation is deemed to be simple and straight-forward, only requiring testing with the FWD device. In addition, the design procedure developed in this study has been also implemented into a Windows-based computer program for fast processing of FWD data and the selection of an appropriate overlay thickness.

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INTRODUCTION

Prior to 1960, most agencies relied heavily on engineering judgment and experience in determining the required overlay thickness for a roadway. Since 1960, the use of nondestructive deflection testing (NDT) devices such as the Benkelman beam, Dynaflect, and falling weight deflectometer (FWD) began to gain wide acceptance due to their ease of operation and the ability to assess the in situ structural integrity. After 1980, more rational methods based on NDT deflection measurements to evaluate the in-situ pavement conditions have gradually developed *[1-6]*.

The current LADOTD overlay thickness design follows the "Component Analysis" method provided in the 1993 AASHTO pavement design guide *[7]*. Neither field NDT nor laboratory fundamental property tests are required with this method. LADOTD pavement engineers often rely on a pre-assigned, parish-based, typical subgrade resilient modulus value (M_r) and a set of table-assumed layer coefficients in determining, respectively, the subgrade strength and the effective structural number (SN) of an existing pavement in an overlay thickness design. Obviously, this procedure will potentially lead to errors in the determined overlay thickness since none of the design values represent actual field conditions. An over estimated M_r or SN value will result in an under-designed overlay thickness (i.e., overlay thickness value smaller than required) that may cause an early failure of a pavement under loading. On the other hand, an underestimated M_r or SN value will produce a over-designed overlay thickness, which should also be avoided by a highway agency because it would allocate more funding into one project that is not necessary.

NDT-deflection based overlay design procedures are generally more accurate than the current method because they capture the actual field pavement conditions. A newly developed Mechanistic-Empirical Pavement Design Guide (MEPDG) includes a design module specifically for the determination of an asphalt overlay thickness, in which in-situ NDT results can be incorporated *[8]*. However, implementing the MEPDG in Louisiana will require a local calibration and verification on those empirical models used in the software. Both the local calibration and verification processes involve a time consuming data collection task that may take several years to complete. Due to an urgent need of a NDT-based overlay design method and a time constraint on implementation of MEPDG, the main propose of this study was to come up a NDT-based overlay thickness design method/procedure for the rehabilitation of flexible pavements in Louisiana. An extensive literature search was conducted to identify NDT-based overlay design procedures currently being utilized by other agencies. Regarding the new mechanistic-empirical design method, this procedure will require several years to implement in Louisiana and is currently under review by a LADOTD committee *[8]*.

Background

There are three design methods commonly used in practice to estimate the required overlay thickness: the effective thickness approach, the deflection approach, and the mechanistic-empirical approach. In general, NDT deflection testing can be incorporated into any of those design methods.

Effective Thickness Approach

The basic concept is that the required thickness of asphalt concrete overlay is the difference between the thickness required for a new full-depth pavement and the effective thickness of the existing pavement. The procedure assumes that as the pavement deteriorates, it behaves as if it were an increasingly thinner pavement because its effective thickness accounts less and less for the expended portion of its total life *[14]*. Because the effective thickness is based on the type, condition, and thickness of each component layer, this method is also called the component analysis procedure *[14]*.

The AASHTO (originally AASHO) pavement design guide was first published as an interim guide in 1972. Updates to the guide were subsequently published in 1986 and 1993; a new mechanistic-based design guide is currently being reviewed and implemented by different state agencies *[8]*. The AASHTO design procedure is based on the results of the AASHO Road Test that was conducted in 1959-1960 in Ottawa, Illinois. Approximately 1.2 million axle load repetitions were applied to specially designed test tracks in the largest road test ever conducted *[22]*.

The 1993 AASHTO overlay thickness design method utilizes the effective thickness approach *[7]*. In the AASHTO method, the required thickness of the asphalt concrete (AC) overlay is a function of the structural capacity required to meet future traffic demands and the structural capacity of the existing pavement, as determined by the following basic design equation:

$$h_{OL} = \frac{SN_{OL}}{a_{OL}} = \frac{SN_f - SN_{eff}}{a_{OL}} \tag{1}$$

where, h_{OL} = required thickness of asphalt overlay, SN_{OL} = required structural number of asphalt overlay, a_{OL} = structural layer coefficient of asphalt overlay, SN_f = structural number required to carry future traffic, and SN_{eff} = total effective structural number of the existing pavement prior to overlay.

The effective design subgrade resilient modulus is required to determine the required structural number (SN_f) through the AASHTO flexible pavement design equation *[7]*. AASHTO provides three methods from which the design M_r values are obtained: (a) laboratory testing, (b) backcalculation from NDT measurements, and (c) approximate estimation using available soil information and relationships developed from a resilient modulus study. Similarly, AASHTO suggests three methods to determine the effective structural number (SN_{eff}): (a) NDT method, (b) condition survey method, and (c) remaining life method. With calculated SN_f and SN_{eff} values, the thickness of overlay can be then determined from equation (1).

The Asphalt Institute MS-17 provided two separate flexible pavement overlay design methods, the effective thickness method and a deflection-based procedure *[9]*. The effective thickness method in MS-17 estimates the overlay thickness as the difference between the thickness required for a new full-depth asphalt pavement and the effective thickness of the existing pavement as provided in the following equation:

$$h_{OL} = h_n - h_e = h_n - \sum_{i=1}^{n} C_i h_i \tag{2}$$

where, h_{OL} = required asphalt overlay thickness, h_n = thickness of new full-depth asphalt pavement; h_e = effective thickness of the existing pavement, h_i = thickness of the ith layer of the existing pavement, C_i = conversion factor associated with the ith existing layer, and n = number of layers in the existing pavement structure.

The conversion factors (C_i) used in equation (2) are empirically estimated based on the existing pavement distress condition and material classification. Additional detailed descriptions of conversion factors for different classifications of paving materials can be found in Table 8-1 of the MS-17 manual *[9]*. As stated in the MS-17 manual, "These convention factors, encompassing most paving materials, are in some degree subjective." Therefore, although the AI effective thickness method is simple to apply, the estimated overlay thickness is very sensitive to the used design conversion factors of each component layer.

Some state DOTs, e.g., Alabama, Virginia, South Carolina, and Maryland, have developed a spreadsheet based program using the FWD in their flexible pavement overlay design procedures based on either the 1993 AASHTO overlay design or Asphalt Institute MS-17 procedures.

The current overlay design method used by LADOTD follows the 1993 AASHTO overlay design method, where the design M_r value is derived from an empirically based parish modulus map, and the SN_{eff} is from the condition survey method. Therefore, no laboratory or field NDT tests are required by the current LADOTD overlay thickness design procedure.

Deflection Approach

The deflection approach method is based on the empirical relationship between pavement deflection and overlay thickness. The basic concept of this method is that larger pavement surface deflections imply a weaker pavement and subgrade, thus, require thicker overlays. The overlay must be thick enough to reduce the deflection to a tolerable amount. Usually only the maximum deflection directly under the load is used *[5]*.

The second method in Asphalt Institute MS-17 manual is based on deflection measurements taken using the Benkelman beam test *[9]*. With the projected overlay traffic, the temperature adjustment factor, and the critical period adjustment factor, the design overlay thickness is obtained from a design chart using overlay traffic and a design deflection indicator called the representative rebound deflection. The basic issues related to the MS-17 deflection based overlay thickness design procedure are summarized as follows *[9], [14]:*

- Deflection Data Measurement: At least 10 deflection measurements should be made for each analysis or a minimum of 20 measurements per mile. Pavement temperatures are measured at the time of deflection measurements so deflections can be adjusted to a standard temperature of 70°F.
- Representative Rebound Deflection: When deflection tests on the analysis section are completed, the recorded pavement rebound deflections are used to determine a representative rebound deflection (RRD):

  $$\delta_{rrd} = (\overline{\delta} + 2s)(F)(C) \tag{3}$$

  where, δ_{rrd} = the representative rebound deflection, $\overline{\delta}$ = the mean deflection, s = the standard deviation, F = the temperature adjustment factor, and C = the critical period adjustment factor.
- Deflection After Overlay (δ_d): The overlaid pavement is considered a two-layer system with the HMA overlay as layer 1 and the existing pavement as layer 2. The representative

rebound deflection is used to determine the modulus of layer 2 using the following equation:

$$E_2 = \frac{1.5qa}{\delta_{rrd}} \tag{4}$$

where, q = the contact pressure and a is the radius of the wheel load on dual tires. The design rebound deflection after overlay (δ_d) is determined as follows:

$$\delta_d = \frac{1.5qa}{E_2}\left(\left\{1-\left[1+0.8\left(\frac{h_1}{a}\right)^2\right]^{-0.5}\right\}\frac{E_2}{E_1}+\left\{1+\left[0.8\frac{h_1}{a}\left(\frac{E_1}{E_2}\right)^{1/3}\right]^2\right\}^{-0.5}\right) \tag{5}$$

where, h_1 = the thickness of the overlay, and E_1 = the modulus of the overlay.

- Overlay Thickness Design: It is assumed that there is a unique relationship between design rebound deflection and the allowable ESAL as represented by:

$$\delta_d = 1.0363(ESAL)^{-0.2438} \tag{6}$$

Given the ESAL for the overlay, δ_d can be determined from equation (6). Given the representative rebound deflection δ_{rrd}, E_2 can be obtained from equation (4). With δ_d and E_2 known and values of q, a and E_1 assumed, the thickness of overlay h_1 can be computed from equation (5).

Similarly, the California Department of Transportation (Caltrans) currently also uses the deflection approach in their overlay designs *[12]*. An overlay design using dense-graded asphalt concrete (DGAC) mixtures in the Caltrans Flexible Pavement Rehabilitation Manual is presented as follows *[12]*:

- Field Deflection Measurement: For all lanes considered for rehabilitation, measure deflection at 80-m intervals in the outside wheel path to obtain 21 deflection measurements per 1.6 lane-kilometer (1 mile). Any NDT tests can be used in the deflection measurement. However, the deflection values measured from devices other than California Deflectometer must be converted to equivalent California Deflectometer values used in the overlay design. The California Deflectometer is a Benkelman Beam based rolling wheel device. Therefore, a relationship between the California Deflectometer deflections and deflections obtained using other NDT devices (e.g., Dynaflect, and FWD) must be constructed before overlay deflection testing.

- The 80th percentile of the California Deflectometer equivalent deflections in the analysis unit are then computed based on the following equations:

$$\bar{x} = \frac{\sum D_i}{n}, \; s = \sqrt{\frac{\sum (D_i - \bar{x})^2}{n-1}}$$

$$D_{80} = \bar{x} + 0.84s \tag{7}$$

where,

$\bar{x}$ = mean deflection for a test section,

D_{80} = 80th percentile of the deflections at the surface for a test section in inches,

S = standard deviation of all deflections for a tee section,

D_i = an individual deflection measurements in the test section, and

n = number of measurements in the test section.

- Tolerable Deflection at the Surface (TDS): The TDS is determined from the Tolerable Deflection Table as shown in Table 1 with the design Traffic Index (TI) and either the thickness of the existing asphalt concrete pavement or the type of base data. The design TI can be determined using the following equation:

$$\text{TI}=9.0\ (\text{ESAL}/10^6)^{0.119} \tag{8}$$

- Calculate the Percent Reduction in Deflection (*PRD*) at the surface:

$$PRD = \frac{D_{80} - TDS}{D_{80}}(100) \tag{9}$$

Note that the Caltrans method uses a relative strength indicator known as the gravel equivalent (*GE*). The *GE* has been related to two main design parameters, namely, traffic loads (N_T in ESALs) and materials strength as given by equation (10) *[12]*.

$$GE = 0.0032 \times TI \times (100 - R)$$

$$TI = 9.0\left(\frac{N_T}{10^6}\right)^{0.119} \tag{10}$$

Determine the increase in GE required reducing D_{80} to the TDS, utilizing the calculated PRD and a design table. It is the amount of gravel that will provide sufficient strength to reduce the deflections to the tolerable level. To determine the overlay thickness, the following conditions are considered:

a) For structural adequacy:

Overlay = *GE*/*Gf*

where, *Gf* = the gravel factor. For a dense-graded asphalt concrete overlay over an existing AC pavement, use a Gf of 1.9 regardless of thickness and *TI*.

b) For reflective cracking:

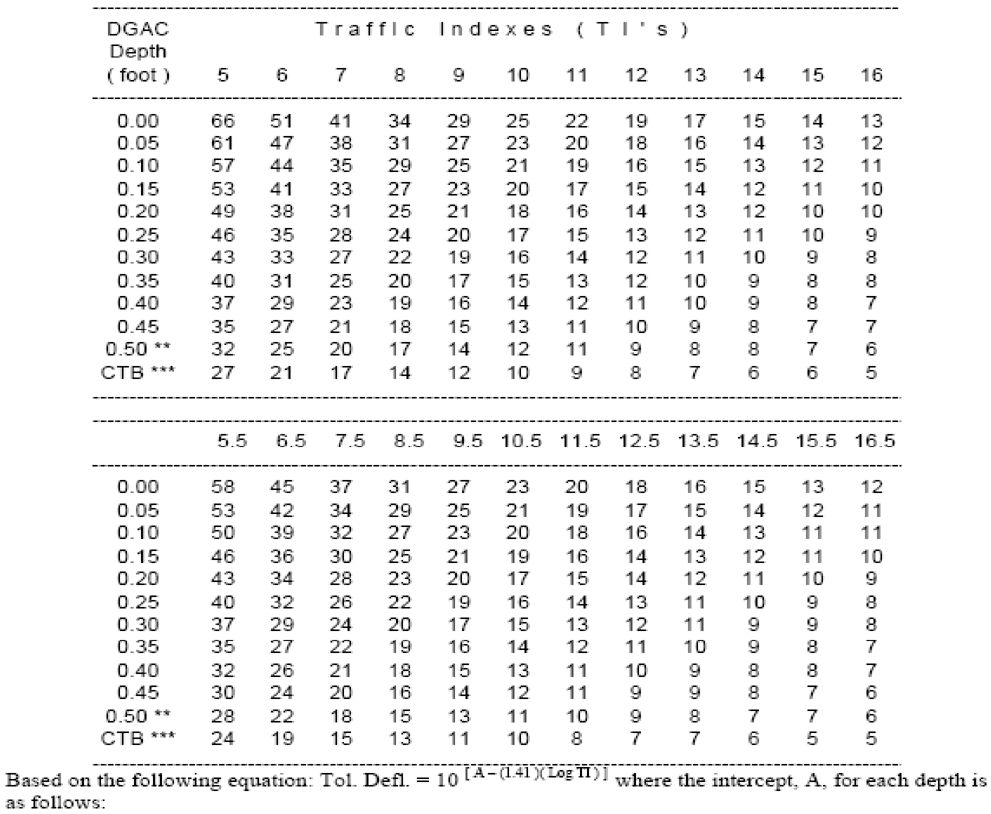
Overlay = a minimum of half the existing AC thickness

c) For ride quality:

Overlay = a minimum of 0.25 ft. placed in two layers

Table 1

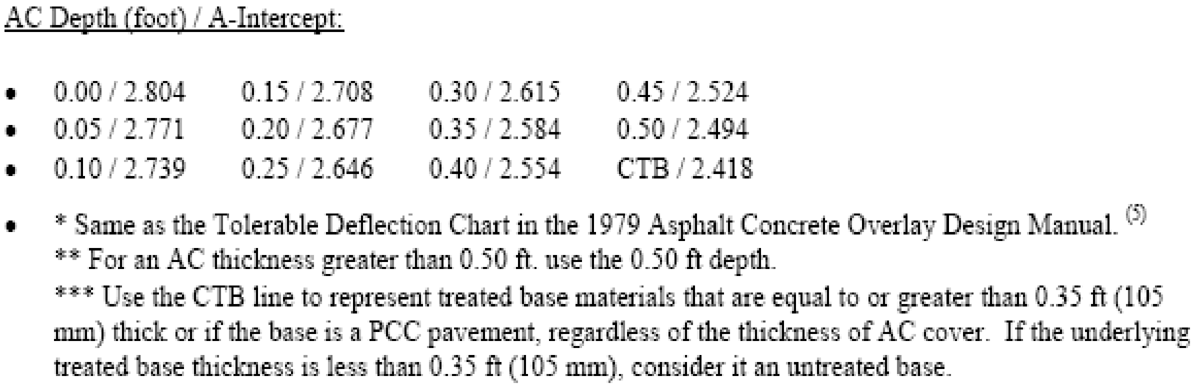
Tolerable deflections (× 0.001 in.) *[11]*



DGAC Depth (foot)	Traffic Indexes (T I ' s) 5	6	7	8	9	10	11	12	13	14	15	16
0.00	66	51	41	34	29	25	22	19	17	15	14	13
0.05	61	47	38	31	27	23	20	18	16	14	13	12
0.10	57	44	35	29	25	21	19	16	15	13	12	11
0.15	53	41	33	27	23	20	17	15	14	12	11	10
0.20	49	38	31	25	21	18	16	14	13	12	10	10
0.25	46	35	28	24	20	17	15	13	12	11	10	9
0.30	43	33	27	22	19	16	14	12	11	10	9	8
0.35	40	31	25	20	17	15	13	12	10	9	8	8
0.40	37	29	23	19	16	14	12	11	10	9	8	7
0.45	35	27	21	18	15	13	11	10	9	8	7	7
0.50 **	32	25	20	17	14	12	11	9	8	8	7	6
CTB ***	27	21	17	14	12	10	9	8	7	6	6	5

	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5
0.00	58	45	37	31	27	23	20	18	16	15	13	12
0.05	53	42	34	29	25	21	19	17	15	14	12	11
0.10	50	39	32	27	23	20	18	16	14	13	11	11
0.15	46	36	30	25	21	19	16	14	13	12	11	10
0.20	43	34	28	23	20	17	15	14	12	11	10	9
0.25	40	32	26	22	19	16	14	13	11	10	9	8
0.30	37	29	24	20	17	15	13	12	11	9	9	8
0.35	35	27	22	19	16	14	12	11	10	9	8	7
0.40	32	26	21	18	15	13	11	10	9	8	8	7
0.45	30	24	20	16	14	12	11	9	9	8	7	6
0.50 **	28	22	18	15	13	11	10	9	8	7	7	6
CTB ***	24	19	15	13	11	10	8	7	7	6	5	5

Based on the following equation: Tol. Defl. = $10^{[A-(1.41)(\mathrm{Log\ TI})]}$ where the intercept, A, for each depth is as follows:



AC Depth (foot) / A-Intercept:

- 0.00 / 2.804 0.15 / 2.708 0.30 / 2.615 0.45 / 2.524
- 0.05 / 2.771 0.20 / 2.677 0.35 / 2.584 0.50 / 2.494
- 0.10 / 2.739 0.25 / 2.646 0.40 / 2.554 CTB / 2.418
- * Same as the Tolerable Deflection Chart in the 1979 Asphalt Concrete Overlay Design Manual. (5)
  ** For an AC thickness greater than 0.50 ft. use the 0.50 ft depth.
  *** Use the CTB line to represent treated base materials that are equal to or greater than 0.35 ft (105 mm) thick or if the base is a PCC pavement, regardless of the thickness of AC cover. If the underlying treated base thickness is less than 0.35 ft (105 mm), consider it an untreated base.

In 1980, LADOTD developed a Dynaflect deflection-based approach for asphalt concrete overlay thickness selection *[1]*. The primary failure criteria selected in the Dynaflect deflection-based approach was the development of fatigue cracking. In the approach, tolerable deflection-traffic load relationships and deflection attenuation properties of asphaltic concrete were developed. A suite of overlay thickness design charts was constructed for overlays of flexible, rigid, and composite pavements, representing the subgrade support conditions and properties of materials used in Louisiana. The design maximum deflection input used in the overlay thickness design charts require correction for the effect of temperature (using the Southgate method) and seasonal subgrade moisture variation (using a Pavement Evaluation Chart developed in the study) *[21]*. This approach is theoretically sound and easy for implementation. However, due to implementing the 1993 AASHTO pavement design method, the developed Louisiana Dynaflect deflection-based overlay design procedure has never been implemented into a routine use.

Mechanistic-Empirical (M-E) Approach

The M-E approach for the overlay design is similar to the design of new pavements. It requires that pavement materials be described by their stiffness and strength at different times of the year. This in turn requires that the stiffness and strength be measured directly in the field or laboratory or that correlation be used to estimate the stiffness and strength from other tests. The design procedures are based on the assumption that a pavement can be modeled as multi-layered elastic or visco-elastic structure on an elastic or visco-elastic foundation. It requires the determination of critical stress, strain, or deflection in the pavement by some mechanistic methods and the prediction of resulting damages by some empirical failure criteria. First, the pavement existing life must be evaluated. Based on pavement condition or remaining life, the overlay thickness is then determined so damages in either the existing pavement or new overlay will be within allowable limits. Several state departments of transportation (DOTs) have developed their own flexible overlay design models using the M-E approach, including Arizona DOT*,* Oregon DOT*,* Washington DOT, and Minnesota DOT *[17], [20], [24],* and *[25]*. These procedures apply the M-E overlay design method using NDT data and develop models that are calibrated to meet the local conditions of each state highway system.

Take the Washington DOT overlay design program as an example. EVERPAVE is a windows-based computer program developed by Washington DOT for the use of flexible pavement overlay design. EVERPAVE is based on the multilayered elastic analysis program, WESLEA (provided by the Waterways Experiment Station, U.S. Army Corps of Engineers), which produces the pavement response parameters, such as stresses, strains, and deformations in the pavement system. The layer moduli required in EVERPAVE are backcalculated from FWD deflection basins using EVERCALC, FWD backcalculation software developed by Washington DOT *[20]*. The determination of the overlay thickness is based on the required thickness to bring the damage levels to an acceptable point under a design traffic condition. Figure 1 shows the design flowchart in the EVERPAVE program. The damage levels are based on two primary distress types–fatigue cracking and rutting–that are the most common criteria for mechanistic analysis-based overlay design.

For fatigue cracking, the Monismith-Finn laboratory fatigue model is selected *[20]*:

$$\log N_f = 14.82 - 3.291\log(\varepsilon_t) - 0.854\log(E_{ac}) \tag{11}$$

where, N_f = loads to failure, ε_t = initial tensile strain, and
E_{ac} = stiffness of AC layer.

For rutting, the Chevron equation is selected:

$$\log N_f = 1.077 \times 10^{18} (\varepsilon_V)^{-4.4843} \tag{12}$$

where, N_f represents the loads that cause a 0.75-in. rut, and
ε_V is the vertical compressive stress on the top of subgrade.

The process of the EVERPAVE overlay design procedure is accomplished in the following sequences, as also shown in Figure 1 *[20]*.

1. Read input data, including initial overlay thickness. The initial overlay thickness is necessary to prove a starting point from overlay thickness determination. The initial overlay must be greater than zero.
2. Adjust pavement materials for seasonal moduli variations.
3. Analyze the pavement system and determine the two failure criteria parameters.
4. Compute allowable repetitions to failure, compare the design traffic with the allowable load repetitions, and calculate the damage ratio for each season.
5. Repeat Steps 2, 3, and 4 for four seasons.
6. Compute the sum of the seasonal damage ratio.
7. If the sum of the damage ratio is less than or equal to one, produce the overlay thickness. Otherwise, increase the overlay thickness and repeat Steps 1 through 7 until the sum of the damage ratio becomes less than or equal to one.

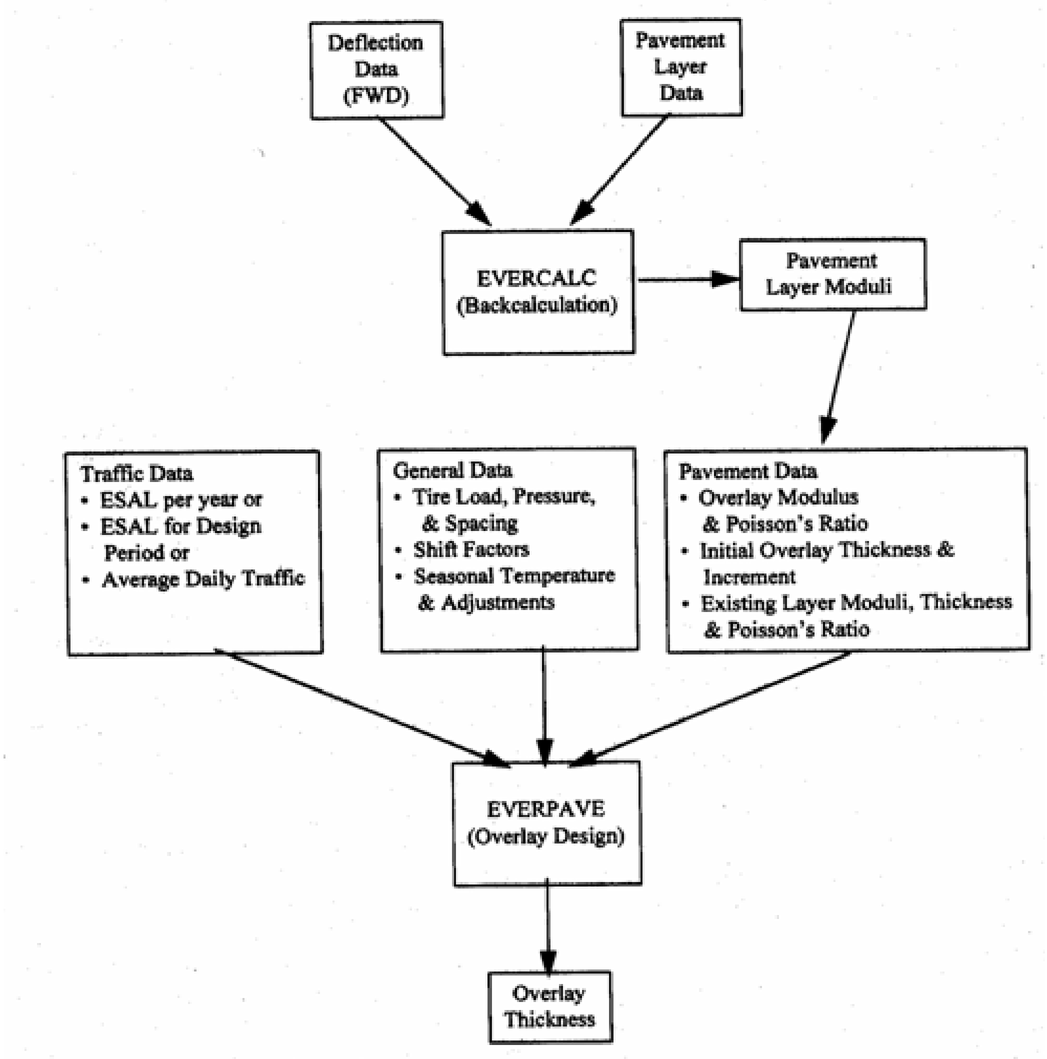


Figure 1
EVERPAVE flow chart *[20]*

E-Mail Survey

During the literature review, an email-based survey was conducted among the state DOTs to find out whether NDT methods are being incorporated into flexible pavement overlay thickness design procedures. The email survey basically asked whether FWD or Dynaflect testing is being incorporated into their overlay thickness design process, and if the answer was “yes,” then the second question asked what specific software (or spreadsheet-based design procedure) they are using for the overlay design. Ten state DOTs who currently use the NDT in their overlay design programs have responded to this survey. Table 2 presents the survey results together with several literature search results.

Table 2
State DOT overlay design methods with NDTs

State	Contact	Comments on NDT Methods
Mississippi	James Watkins	The FWD is used for overlay designs. The design module from Dynatest's ELMOD 5 software is used for overlay designs.
Washington	Linda Pierce	They use the FWD in overlay design. They have their own software package called EVERSERIES. It does backcalculations, stress analysis, and overlay design. The package is free as well as the manual.
Minnesota	Dave VanDeusen	They use the FWD in overlay design. They have their own software package called MNPAVE. The package and manual are free.
Virginia	Trenton Clark	They use the FWD in design. They have developed a software package called ModTAG and use it for analysis and design. The software is available for free but technical support must be paid for.
North Carolina	Judith Corley-Lay	They use the FWD in design. Their design is based on deflections and use asphalt institutes deflection criteria for overlays. They developed a spreadsheet to perform related computations.
South Carolina	Andy Johnson	They use the FWD in overlay design. They developed a spreadsheet based on the AASHTO two-layer design and the asphalt institute.

Table 2 (continued)
State DOT overlay design methods with NDTs

State	Contact	Comments on NDT Methods
Alabama	Scott George	They use the FWD for maintenance overlays. They developed a spreadsheet based upon the 1993 AASHTO design guide equations and use DARWin also.
Maryland	Tim Smith	They use the FWD in overlay designs. They use Modtag for analysis and overlay design.
Illinois	Charles Wienrank	Use the FWD only for load transfer and monitoring. They do not use it for design purposes. They have a standard overlay policy.
Arkansas	Jennifer Williams	They use the FWD in their design process. They have developed a program called Road Hog for pavement design. She will transmit the program and manuals to us for our use.
Idaho	Literature *[10]*	Developed an M-E based flexible overlay design program-WinFlex. FWD deflection basins used for backcalculation of layer moduli.
California	Literature *[11]*	Deflection-based empirical overlay thickness design. Deflection measured from California Deflectometer, Dynaflect or FWD.
Oregon	Literature *[24]*	M-E based method, back-calculated modulus using FWD.
Texas	Literature *[22]*	Flexible Pavement System (FPS-19W) uses back-calculated modulus to characterize the pavement layer strength (stiffness) based on FWD deflection measurements. The MODULUS 5.1 backcalculation procedure generates the input layer moduli. The WESLEA linear elastic computer program, embedded within FPS19, computes pavement responses. The main design parameter is the Surface Curvature Index computed at the midpoint of a set of dual tires loaded to 40 kN (9,000 lb.).

OBJECTIVE

The main objective of this study was to establish a flexible pavement overlay thickness design method based upon (1) Louisiana in-situ pavement conditions and (2) NDT methods, specifically the FWD and/or Dynaflect.

SCOPE

Fifteen overlay rehabilitation projects were selected for this study. These projects were strategically located throughout Louisiana with different traffic levels. At each selected project, NDT deflection tests including the FWD and Dynaflect were performed at a 0.1-mile interval and on both traffic directions. Six NDT-based overlay design methods–Louisiana 1980 Dynaflect procedure, Asphalt Institute (AI) MS-17, Arkansas ROADHOG, ELMOD 5, EVERPAVE, and the 1993 AASHTO NDT procedure–were selected and used in the overlay thickness design analysis. In addition, the newly developed MEPDG software was also included in the analysis. It should be noted that local calibration of those selected NDT overlay design methods were not in the scope of this research study. Instead, a modified NDT overlay design method was developed in this study based upon testing and research conducted on Louisiana highways. Finally, the economic benefits of using the developed NDT overlay design method were quantified through the construction and life-cycle cost analyses.

METHODOLOGY

To achieve the objective of this research study, the following general methodology and analysis procedures were performed:

- Selected 15 overlay rehabilitation projects from LADOTD's overlay letting list based on different subgrade types and three (low-, medium-, and high-volume) traffic levels. Performed NDT (FWD and Dynaflect) deflection tests on each of selected projects.
- Conducted a comprehensive literature review and an email survey among other state DOTs to find out whether NDT testing is being incorporated into their overlay thickness design procedures. Six NDT-based overlay design procedures (or software) were identified, which include: (1) Kinchen-Temple Dynaflect deflection-based procedure or Louisiana 1980 Deflection-based procedure*,* (2) EVERPAVE by Washington DOT*,* (3) Arkansas ROADHOG*,* (4) Asphalt Institute MS-17 deflection approach, (5) the 1993 AASHTO pavement design guide NDT procedure*,* and (6) ELMOD 5 by Dynatest *[1], [20], [25], [9], [7],* and *[26].*
- Performed overlay thickness design for the four Phase I rehabilitation projects based upon (1) the NDT deflections and (2) the six selected NDT overlay design procedures. Analyzed the overlay thickness results and compared to those obtained from the LADOTD component analysis method as well as those obtained from the newly developed MEPDG software.
- Evaluated the Dynaflect-deflection based Louisiana Pavement Evaluation Chart and developed a FWD deflection-based overlay thickness design procedure for flexible pavement overlay thickness design in Louisiana.
- Developed a Visual Basic computer program for automating the proposed FWD based overlay design procedure.
- Performed cost-benefit analyses on the Phase II rehabilitation projects.
- Prepared a final report that documented and summarized the study results.

General Information on Projects

A total of 15 overlay rehabilitation projects were selected in this study. These projects were further divided into Phase I and Phase II analyses. Figure 2 presents the project locations throughout the state. Among them, the four projects highlighted with the hatch-shaded cycles on the map were used in the Phase I study, whereas, the remaining 11 projects were analyzed in Phase II.

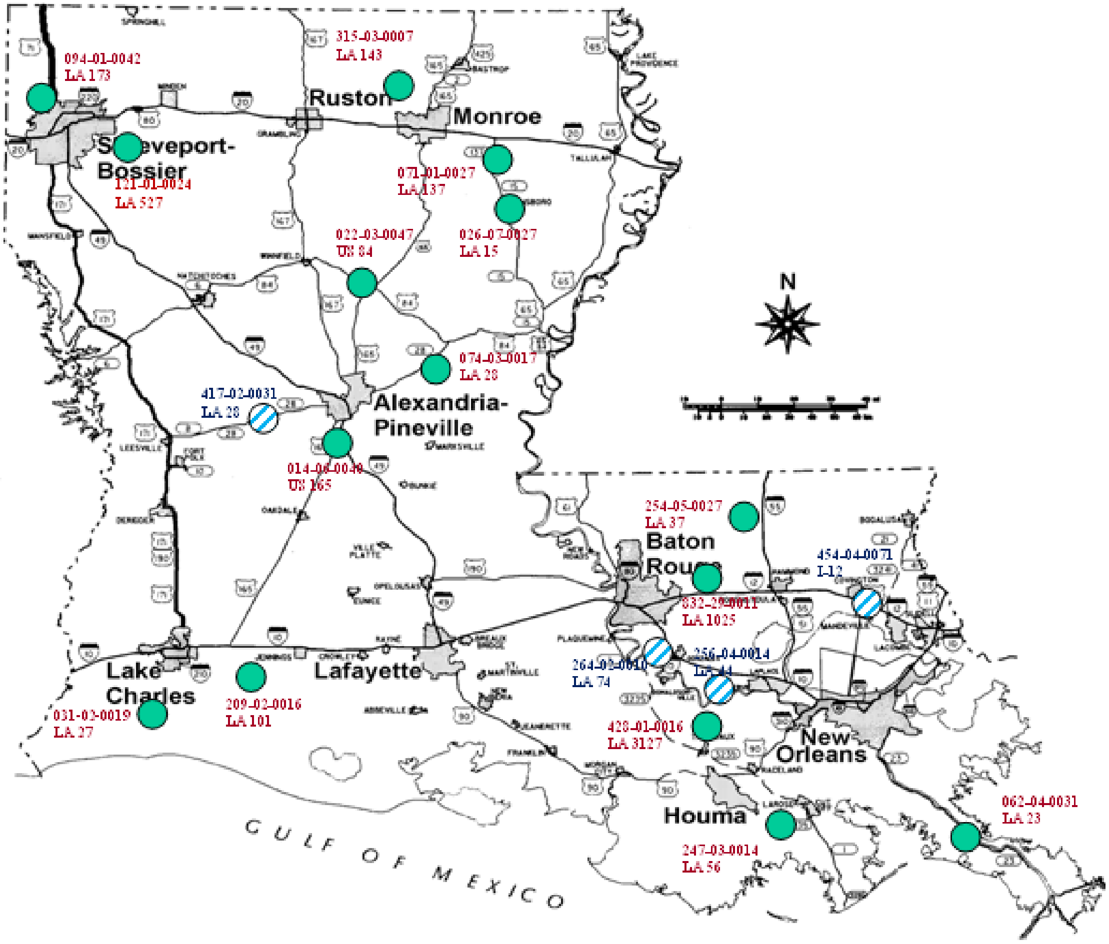


Figure 2
Location of pavement projects

The general overlay design inputs of selected projects are presented in Table 3. The existing pavement structures and the corresponding LADOTD overlay thicknesses are listed in Table 4. All design information in Table 3 and Table 4 were retrieved from the LADOTD's *AC Overlay of AC Pavement* design sheets obtained from the DARWin Pavement Design and Analysis System. As shown in Table 3, the average daily traffic (ADT) of the selected projects ranges from 1,100 to 45,100; the subgrade modulus selected from the LADOTD's parish map varies from 8,023 psi to 10, 278 psi. Because of the random selection process and their strategic locations throughout the LADOTD pavement network, the selected projects are believed to have covered the majority of the Louisiana flexible pavement condition in a pavement rehabilitation project.

Table 3
General project information

Route Name	Road Classification	Parish	Length (miles)	ADT	Design EASL	Design M_r (psi)*
Phase I						
LA 28	Rural Arterial	Rapides	6.7	5,700	1,512,993	9,916
LA 44	Rural Collector	St. James	7.54	3,300	353,256	8,023
LA 74	Rural Collector	Ascension	3.35	7,700	818,073	8,400
I-12	Urban Interstate	St. Tammany	10.541	45,100	2,4399,600	9,200
Phase II						
LA 173	Rural Collector	Caddo	6.416	2,609	363,342	10,278
LA 527	Rural Collector	Bossier	3.788	1,892	192,296	8,797
LA 143	Rural Collector	Union	6.85	4,626	681,672	10,278
LA 137	Rural Collector	Richland	7.11	3,450	845,472	9,549
LA 27	Rural Collector	Cameron	16.96	2,400	239,210	9,176
LA 101	Rural Collector	Jeff Davis	3.115	2,600	267,529	8,413
US 84	Rural Arterial	Winn	8.004	1,100	232,221	9,200
US 165	Rural Arterial	Rapides	7.311	8,400	1,344,639	9,916
LA 15	Rural Collector	Franklin	5.46	10,100	1,379,645	9,916
LA 28-2	Rural Arterial	Lasalle	7.293	3,300	794,116	9,200
LA 3127	Rural Collector	St. James	5.58	1,313	295,705	8,023
LA 37	Rural Collector	St. Helena	5.44	2,300	496,816	9,549
LA 1025	Rural Collector	Livingston	6.26	4,900	297,029	9,500

Note: * Design M_r values are the subgrade moduli obtained from the Louisiana Parish M_r map.
All roadways have two lanes except that I-12 is a four-lane divided roadway.

Table 4
Existing pavement structure and LADOTD overlay thickness design

Route #	Length (miles)	Surface		Base		Subgrade Type
		Type	Thickness	Type	Thickness	
LA 28	6.7	AC	5"	Soil Cement		Varying Types
LA 44	7.54	AC	9"	HVY CL	18"	Varying Types
LA 74	3.35	AC	6"	Soil Cement	4"	Varying Types
I-12	10.541	AC	15"	Soil Cement	9"	Varying Types
LA 173	6.416	AC	3.5"	Soil Cement	7"	Varying Types
LA 527	3.788	AC	6.5"	Soil Cement	6"	Varying Types
LA 143	6.85	AC	4.5"	Soil Cement	8"	Varying Types
LA 137	7.11	AC	7.18"	AB	8"	Varying Types
LA 27	16.96	AC	8"	Shelly SDY LM	9"	STY CL
LA 101	3.115	AC	8.5"	Shelly SDY LM	4"	STY CL
US 84	8.004	AC	4"	Soil Cement	8"	Varying Types
US 165	7.311	AC	10"	Soil Cement	8.5"	Varying Types
LA 15	5.46	AC	8.75"	Soil Cement	7.5"	Varying Types
LA 28-2	7.293	AC	8.5"	Soil Cement	8"	Varying Types
LA 3127	5.58	AC	6"	Soil Cement	8"	Sand
LA 37	5.44	AC	4"	Soil Cement	9"	Varying Types
LA 1025	6.26	AC	4"	Soil Cement	8"	Varying Types

Field Testing

Field testing of this study included FWD and Dynaflect deflection tests. Both tests were performed at the same selected locations with FWD tests conducted first. In each project, a 3-mile long section was chosen for field testing. The deflection tests were conducted bi-directionally at 0.1-mile intervals on the right wheel path of the selected lane or the outside lane of a four-lane highway. Pavement mid-depth temperatures were measured during deflections tests. It is noted that in-situ pavement thicknesses of Phase I projects were also measured during testing. In addition, existing pavement conditions were surveyed using a LTRC multi-functional digital highway data vehicle. Each of the testing devices used are briefly described below.

Dynaflect

Dynaflect is a trailer mounted device (Figure 3a), which induces a dynamic load on the pavement and measures the resulting deflections by five geophones, spaced under the trailer at 1-ft. (0.305-m) intervals from the application of the load. The pavement is subjected to

1000 lbf (4.45 kN) of dynamic load produced by two counter rotating unbalanced flywheels rotated at a frequency of 8 Hz. The cyclic force is transmitted vertically to the pavement through two steel wheels spaced 20 in. (50.8 cm) from center to center (Figure 3a).

FWD

The FWD is a trailer-mounted device (Figure 3b). The equipment automatically lifts a weight to a given height and delivers an impulse load to the pavement. The weight is dropped onto a 5.91-in. circular load plate with a thin rubber pad mounted underneath. A load cell measures the force or load applied to the pavement under the plate. A Dynatest 8002 model FWD device was used with nine sensors spaced at 0, 8, 12, 18, 24, 36, 48, 60, and 72 in., respectively. FWD deflection data were obtained from a target load of 9000 lb. and used in the analysis of this study.

(a) Dynaflect **(b) Dynatest 8002 FWD**

Figure 3
Non-destructive testing devices

Condition Survey

A detailed condition survey was performed on Phase I project sites using a multi-functional digital highway data vehicle available at LTRC, Figure 4. The automated system of this vehicle provides high-resolution digital images for pavement surface (cracking) and longitudinal and transverse profiling (as reported by International Roughness Index and rut depth).

Figure 4
LTRC multi-functional digital highway data vehicle

Overlay Thickness Design Methods

A brief description of each selected overlay design method used in this study is presented in the following sections.

Current LADOTD Method

The current LADOTD overlay design method follows the component analysis procedure described in the 1993 AASHTO pavement design guide. To determine the SN_{eff}, layer coefficients for existing pavement layers are chosen from a pre-defined layer coefficient table. Each parish is pre-assigned one representative design M_r value, referred to as the "parish-map modulus." This M_r value is used in the determination of SN_f in equation (1).

The 1993 AASHTO NDT-Based Procedure

As described above, the 1993 AASHTO NDT-based overlay design procedure requires both the design M_r and effective structural number. SN_{eff} and M_r values are backcalculated from NDT measurements acquired from a device such as the FWD. In fact, the 1993 design guide provides the following equations for backcalculation of SN_{eff}:

$$M_R = \frac{0.24P}{d_r r} \qquad (13)$$

$$D_1 = 1.5\,pa\left\{\frac{1}{M_R\sqrt{1+\left(\frac{D}{a}\sqrt[3]{\frac{E_p}{M_R}}\right)^2}} + + \frac{\left[1-\frac{1}{\sqrt{1+\left(\frac{D}{a}\right)^2}}\right]}{E_p}\right\} \tag{14}$$

$$SN_{eff} = 0.0045D\sqrt[3]{E_p} \tag{15}$$

where,
M_r = backcalculated subgrade resilient modulus, psi;
D_1 = deflection measured at the center of the FWD plate (and adjusted to 68°F), inches;
SN_{eff} = effective structural number of an existing pavement;
E_p = effective modulus of all pavement layers above the subgrade, psi;
P = applied load, lb.;
p = FWD load plate pressure, psi;
d_r = deflection at a distance r from the center of FWD plate, in.;
r = distance from center of load, in.;
a = FWD load plate radius, in.; and
D = total thickness of pavement layers above the subgrade, in.

Asphalt Institute MS-17 Deflection Method

As stated earlier, the second method in the AI MS-17 manual is the Benkelman beam deflection based overlay design test *[9]*. With the projected overlay traffic, temperature adjustment factor, and critical period adjustment factor, the design overlay thickness is obtained from a design chart in which a unique relationship has been established for the design rebound deflection, allowable ESALs, and overlay thickness. This method was used in the overlay design based on a relationship between deflections measured from the Benkelman beam and FWD as described in the following equation:

$$BB = 1.61\ D1 \tag{16}$$

where, BB = Benkelman beam measured deflection and
D1 = center deflection of FWD.

Louisiana 1980 Method

In 1980 LADOTD developed a deflection based overlay thickness design guide using Dynaflect measured deflections *[1]*. Due to the implementation of the AASHTO pavement design procedure at that time, it was not implemented for routine use. In the guide, a suite of overlay thickness design charts was constructed for overlays of flexible, rigid, and composite pavements, representing the subgrade support conditions and properties of materials used in Louisiana. The overlay designs are performed by entering charts with the projected traffic load (ESALs), subgrade strength, and temperature-corrected Dynaflect deflections. Selected deflection levels are chosen based on the highway classification and deflection percentiles. For more details refer to Kinchen and Temple's final report *[1]*.

ROADHOG Method

ROADHOG is an Excel spreadsheet-based overlay design computer program. It was developed based on research results conducted for the Arkansas State Highway and Transportation Department (AHTD) *[25]*. The ROADHOG procedure is generally similar to the 1993 AASHTO NDT-based procedure except that the SN_{eff} in ROADHOG is determined based on a relationship between SN_{eff} and Delta-D [equation (17)]. *Delta-D* represents the difference between the FWD surface deflection measured directly under the load (the maximum deflection) and the deflection measured at a distance from the applied load equal to the thickness of the pavement structure *[25]*.

$$SN_{eff} = 0.3206\ (Delta\text{-}D)^{-0.42} \times (pavement\ thickness)^{0.8175} \tag{17}$$

ELMOD 5 Method

ELMOD is an acronym for Evaluation of Layer Moduli and Overlay Design *[26]*. The ELMOD 5 program is a mechanistic-empirical based approach for overlay thickness design. It includes a FWD backcalculation module based on the Odemark-Boussinesq method. In an overlay design using ELMOD 5, the required inputs include the predicted future traffic, backcalculated layer moduli, seasonal variation parameters, and design criteria for both fatigue cracking and permanent deformation. Due to lack of data, ELMOD default values were selected for both seasonal variation parameters and the design criteria. Basically, the default design criteria in ELMOD 5 are the fatigue cracking and rutting equations used in the Asphalt Institute MS-1 design manual *[26]*. The overall overlay thickness for each testing point was determined with the appropriate reliability for the project.

EVERPAVE Method

As introduced earlier, EVERPAVE is a flexible pavement overlay design computer program based on the mechanistic-empirical analysis procedure. EVERSTRS is a multilayered elastic analysis program. EVERCALC is a FWD modulus backcalculation software. All three computer programs were developed by the Washington State Department of Transportation (WSDOT). EVERPAVE uses EVERSTRS (for critical pavement responses under load), EVERCALC (for layer moduli), and certain pavement failure criteria to estimate AC overlay thicknesses *[20]*. The determination of the overlay thickness is based on the required thickness to bring the damage levels to an acceptable level under a design traffic condition. The traffic input is in terms of 18,000 lb. ESALs. The damage levels are based on two primary distress types, fatigue cracking and rutting, which are the most common criteria for mechanistic analysis based overlay design. The EVERPAVE program is also capable of considering seasonal variations and stress sensitivity of the pavement materials.

MEPDG Version 1.0 Method

The NCHRP Project 1-37A was sponsored by the AASHTO Joint Task Force on Pavements, NCHRP, and FHWA to develop an M-E-based pavement design guide. MEPDG was completed and released to the public for review and evaluation in 2004. A formal review of MEPDG was conducted by the NCHRP under Project 1-40A. Project 1-40D resulted in Version 1.0 of the MEPDG software and an updated design guide document. Version 1.0 of the software was submitted to the NCHRP, FHWA, and AASHTO in April 2007 for further consideration as an AASHTO provisional standard and efforts are currently underway on Version 2.0 of the software *[29]*.

The MEPDG software Version 1.0 was used to analyze the overlay design results determined by the proposed and current LADOTD methods in this study *[29]*. The MEPDG software needs sophisticate inputs and most are still not available in Louisiana. In this study, the default Level 3 input values suggested by the MEPDG software were selected in the analysis, except traffic, climate, pavement thickness, and modulus values for the base and subgrade materials (those modulus values were backcalculated from FWD deflections). Additional details of MEPDG can be referred to elsewhere *[29]*.

DISCUSSION OF RESULTS

Analysis of Phase I Projects

Condition Survey Results

The condition survey data, obtained from the LTRC Multi-functional Digital Highway Data Vehicle, included digital cracking image, rut depth, and IRI. Note that each project was considered as two sub-projects in the analysis for different traffic directions. Figure 5 shows a typical field cracking photo for each project considered. The measured rut depth and IRI values are summarized in Table 5.

As shown in Figures 5e-h, cracks observed on existing pavements of LA 74 and LA 44 were fairly severe and continuously distributed throughout the entire project length. Most of the cracks were severe fatigue cracks of aged asphalt pavement. On the other hand, Figures 5a-d indicate that cracks on both I-12 and LA 28 were scattered, isolated, and less severe in most locations. As shown in Table 5, the average rut depths for all projects were found less significant, and ranged from 0.18 to 0.27 inch. However, the standard deviations of rut depths for LA-74W, LA-74E, and LA-44N were found significantly high (ranged from 0.13 to 0.15 inch), much greater than variations for other projects. This suggests that some severe localized rutting areas exist on those pavements. As expected, the combination of surface distresses directly reflects the surface riding characteristics of the existing pavements. From Table 5, the average IRI values of I-12W and I-12E were about 70 inch/mile, followed by LA28 two sections of about 110 inch/mile. The average IRI values for the other four pavement sections (in LA74 and LA44) were more than 150 inch/mile, indicating a very rough riding surface.

Condition survey results mainly provide an indication of functional conditions for the existing pavements, not the pavement structural characteristics. Based on the existing pavement functional conditions, functional overlays for existing pavements of LA 74 and LA 44 are apparently most urgently needed, followed by LA 28, and then I-12. However, in a pavement structural overlay design, the pavement structural characteristics (the strength) of an existing pavement must be pre-estimated, which in this study will be determined using the NDT deflection methods as outlined in the following section.

(a) I-12W

(b) I-12E

(c) LA-28 W

(d) LA-28 E

(e) LA-74 W

(f) LA-74 E

(g) LA-44 S

(h) LA-44 N

Figure 5
Project cracking information survey

Table 5
Summary of condition survey on rutting and surface roughness

Project	Rut Depth (inch)		IRI (inch/mile)	
	Average	Std.	Average	Std.
I-12 W	0.26	0.03	71	14
I-12 E	0.27	0.04	76	44
LA-28 W	0.20	0.06	114	27
LA-28 E	0.18	0.07	115	21
LA-74 W	0.21	0.13	216	86
LA-74 E	0.23	0.15	167	57
LA-44 S	0.23	0.07	224	68
LA-44 N	0.24	0.14	198	54

Note: 1 inch = 25.4mm, 1 inch/mile = 0.0159 m/km, Std. – Standard Deviation.

NDT Results

As stated, the structural conditions of existing pavements were evaluated using two NDT deflection methods (FWD and Dynaflect) in this study. Due to different traffic loading histories, the structural conditions on two traffic directions may be different, thus, need to be measured separately.

FWD Results. Figure 6 presents variations of FWD deflections D1 and D9 for the four projects in Phase I. For the ease of comparison, all FWD deflections have been normalized to a standard load of 9,000 lb. It is known that pavement surface deflection is inversely related to its strength or in-situ modulus. A high surface deflection value indicates a weak pavement structure including the subgrade. Generally speaking, D1 reflects the overall pavement structure strength and D9 indicates the in-situ modulus of the subgrade *[27], [28]*. As shown in Figure 6, D9 values within each project are relatively consistent on both traffic directions. This indicates that subgrade strengths on both traffic directions are similar. By applying the AASHTO NDT subgrade modulus (i.e. equation (13), the average subgrade moduli for I-12, LA 28, LA 74, and LA 44 are 22.1, 6.8, 4.6, and 4.5 ksi, respectively. As compared to the parish map M_r values shown in Table 3, the in-situ backcalculated M_r values differ significantly.

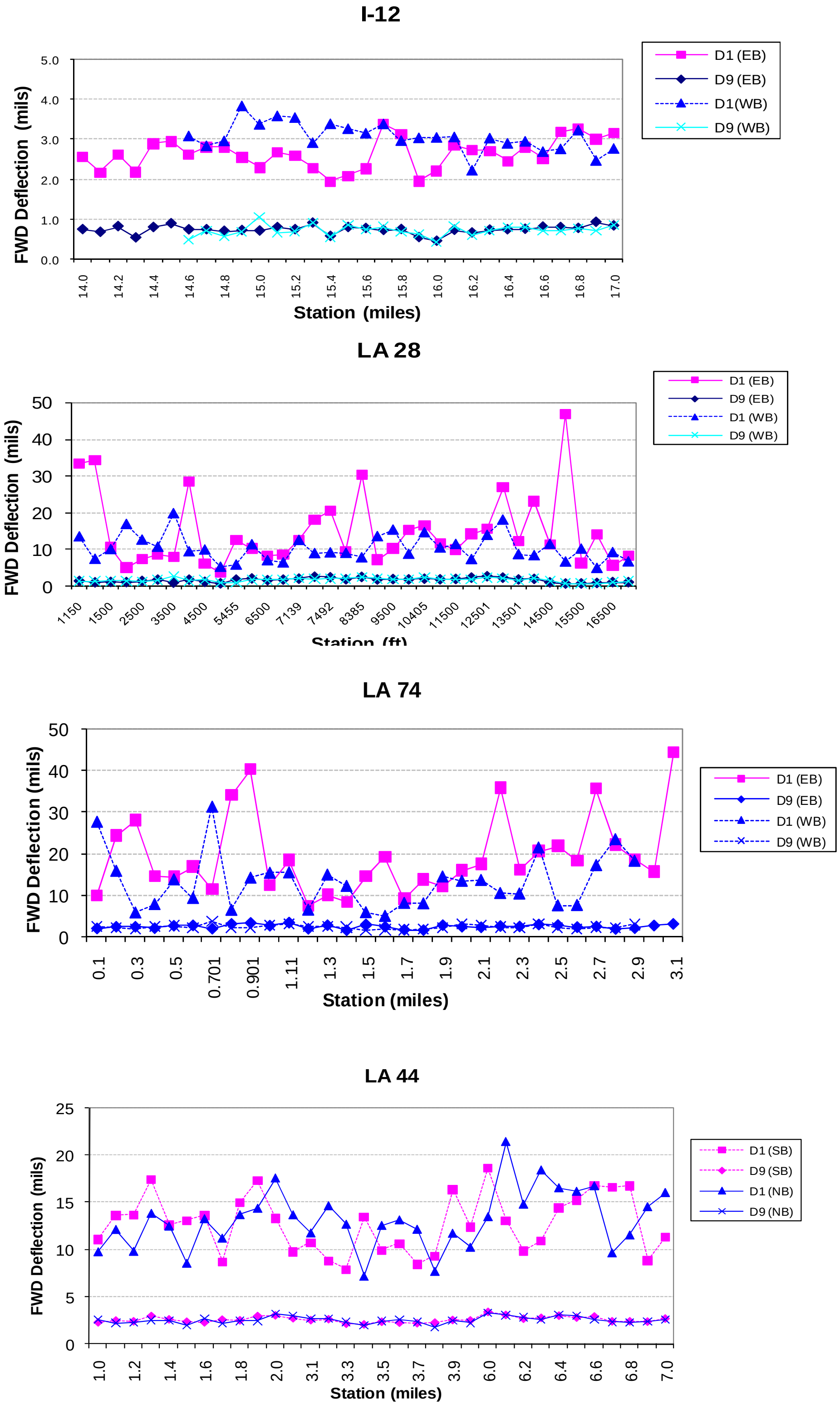


Figure 6
Comparison of Phase-I FWD deflections

The average D1s on I-12, LA 28, LA 74, and LA 44 are 2.85, 12.55, 16.29, and 12.94 mils, respectively. In terms of overall pavement structure strength, the ranking of existing pavements from high to low would be I-12, LA 28, LA 44, and LA 74. This is as expected since the ranking results matched well with the layer thickness configurations of the pavements as shown in Table 4. However, the D1-values varied considerably within each project length. For instance, the standard deviation of D1s in LA-74 E is as high as 9.6 mils. Such deflection variation reflects in-situ pavement strength variation along its project length, which could have resulted from the construction variation in layer thicknesses, differing severity in surface distresses, and/or environmental influences such as pavement temperature differences during FWD testing. The D1-values also varied in different traffic directions. For instance, the average D1-value for LA-74E is 19.43 mils, which is significantly higher than that of 13.15 mils in LA-74W. This appears to indicate that, for each traffic direction, the pavement of LA 74 requires different overlay thicknesses based on the in-situ pavement conditions. Similarly, large directional variations of D1s are observed in LA 28, whereas, such variations for I-12 and LA 44 pavements are relatively small. Table 6 presents a statistic summary of FWD deflections for the four projects evaluated in Phase I.

Table 6
FWD deflection variations

Project	D1 (mils)		D9 (mils)	
	Average	Std.	Average	Std.
I-12 W	3.07	0.35	0.73	0.13
I-12 E	2.64	0.38	0.74	0.10
LA-28 W	10.41	9.82	1.65	0.47
LA-28 E	14.69	3.62	1.70	0.50
LA-74 W	13.15	6.58	2.22	0.48
LA-74 E	19.43	9.62	2.48	0.50
LA-44 S	12.72	3.04	2.58	0.32
LA-44 N	13.16	3.11	2.52	0.36

Dynaflect Results. Figure 7 presents average estimated structural numbers (SN_{eff}) for the existing pavements of Phase-I projects estimated from Dynaflect test results. The higher the SN_{eff} values, the higher the overall structure strengths of existing pavements. Table 7 presents the variation of SN for each project evaluated. As shown in Table 7, the average SN values for I-12, LA 28, LA 74, and LA 44 are 6.4, 3.0, 2.5, and 3.5, respectively.

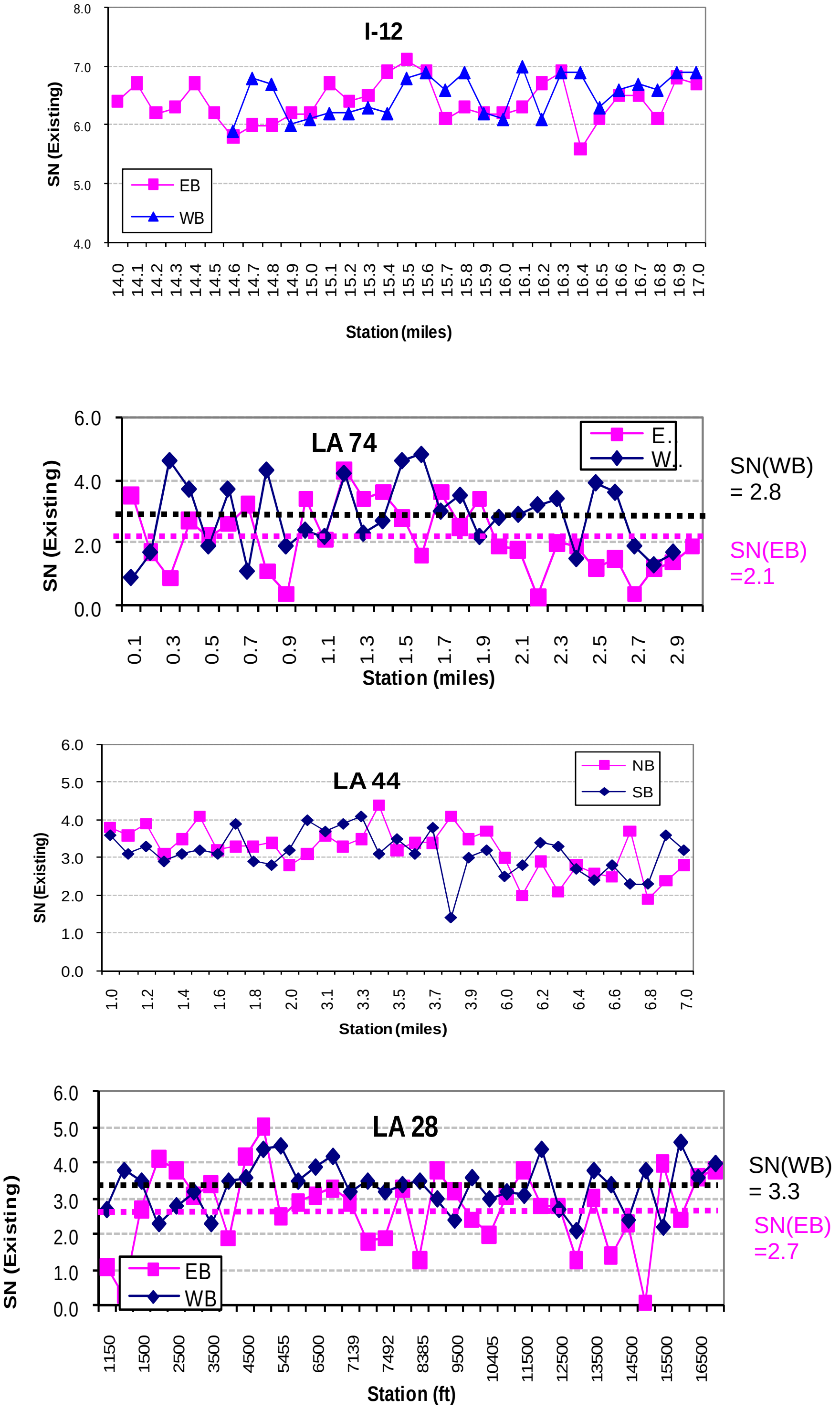


Figure 7

Dynaflect estimated SN values of Phase-I projects

Table 7
SN variations

Project	Traffic Directions	SN_{eff}		p-value*
		Average	Std.	
I-12	WB	6.3	0.3	0.239
	EB	6.3	0.4	
LA-28	WB	3.3	0.7	0.0062
	EB	2.7	1.1	
LA-74	WB	2.8	1.1	0.026
	EB	2.1	1.1	
LA-44	SB	3.0	0.5	0.572
	NB	3.1	0.6	

Note: p-value represents the probability associated with a Student's t-Test for determining if two averages of SNeff (for two traffic directions of each project) are the same or different from each other. If p-value > 0.05, then at a 95% confidence level, the SN averages are equal; if p-value < 0.05, the two average values are not equal at a 95% confidence level.

Similar to those FWD results, SN values varied within each project length and also differed in two traffic directions. As shown in Table 7 (p-values), significantly different SNeff values are observed in two traffic directions for LA 28 and LA 74 (Figure 7). In general, Dynaflect results confirm the aforementioned FWD D1 results, indicating that existing structure strengths on one traffic direction may be significantly different from that on the other direction. Individually speaking, the greatest SN difference can be as high as 5.0 of SN unit.

Overlay Thickness Design Results

Effective Thickness-based Method. Three overlay design methods considered in this study were based on the effective thickness method. They are the current LADOTD method, ROADHOG, and the 1993 AASHTO NDT procedure. Table 8 presents the overlay thickness design results from these methods. It is noted that the reliability level in the overlay design is based on Louisiana roadway classification, which is suggested by the current LADOTD overlay design method. As shown in Table 8, the overlay thicknesses determined by both the AASHTO NDT procedure and ROADHOG program were generally lower than those values obtained from the current LADOTD method with some exceptions (i.e, projects LA-74E and LA 44). Also, the overlay thicknesses determined from the ROADHOG program were similar to that from the AASHTO NDT procedure. The different design thickness results between NDT-based overlay design methods and the current LADOTD method are expected because they were based on in-situ pavement conditions. However, both the AASHTO NDT procedure and ROADHOG program call for empirical relationships in determination of the SN_{eff} values, as described in the previous section. Therefore, the more appropriate method to be used in Louisiana pavement conditions cannot be determined without local calibration.

Table 8
Overlay design results using the effective thickness methods

Project	Classification	Reliability (%)	(1) S_0	Design ESALs	(2)ΔPSI	Overlay thickness (in.)		
						DOTD	AASHTO	ROADHOG
I-12 W	Rural Principal Arterial Interstate	97	0.47	24,399,600	1.5	3.4	0.0	0.0
I-12 E						3.4	0.0	0.0
LA-28 W	Rural Principal Arterial Other	95		1,512,993	1.8	3.3	0.5	0.9
LA-28 E						3.3	2.0	2.2
LA-74 W	Rural Major Collector	85		819,101	2	2.4	1.3	0.2
LA-74 E						2.4	2.7	0.7
LA-44 S	Rural Major Collector	85		353,256	2	0.0	0.0	0.6
LA-44 N						0.0	0.0	0.8

Note: (1) S_0 = combined standard error of the traffic prediction and performance prediction;
(2) ΔPSI = different between the initial design serviceability and the design terminal serviceability index.

Deflection-Based Method. Table 9 presents overlay design results from the AI MS-17 deflection based method. In general, the overlay thicknesses determined by the MS-17 deflection method were all smaller than those thickness values obtained from the current LADOTD method. As shown in Table 9, to use the MS-17 method, the FWD measured deflections have to be first translated into Benkelman beam deflections. Since the correlation between FWD and Benkelman beam deflections has not been verified based on Louisiana pavement conditions, a direct use of such a relationship may lead to unpredictable errors. Interesting to note, although the fundamental methodology using in the MS-17 deflection method is completely different from the effective thickness method, the required overlay thicknesses were found quite similar to the values determined from the 1993 AASHTO NDT procedure as shown in Table 8.

Table 9
Overlay design results using AI deflection method

Project	Average D_1 (mils)	Std. D_1 (mils)	Temperature Correction	RRD (mils)	Overlay Thickness (in.)
I-12 W	3.071	0.349	0.85	5.159	0.0
I-12 E	2.646	0.385	0.9	4.951	0.0
LA-28 W	10.444	3.607	0.85	24.164	0.0
LA-28 E	14.752	9.802	0.82	45.356	2.5
LA-74 W	13.141	6.495	0.9	37.865	1.0
LA-74 E	19.453	9.54	0.82	31.591	2.2
LA-44 S	12.708	2.985	0.83	24.961	0.0
LA-44 N	13.171	3.077	0.8	24.891	0.0

Note: D_1= Center deflection of FWD; RRD=Representative rebound deflection converted from FWD

Table 10 presents the overlay design results using the Louisiana 1980 deflection method. In this method, a temperature-corrected Dynaflect deflection and backcalculated subgrade modulus were used as the inputs in the overlay thickness design chart developed by Kinchen and Temple [1]. Again, the design overlay thickness using the Louisiana 1980 method also differs significantly from the current LADOTD method, but more closely relates to the results obtained from other NDT methods above.

Table 10
Overlay design results using Louisiana 1980 deflection method

Project	Average W_1* (mils)	Std. W_1 (mils)	Subgrade Modulus, Es (ksi)	Traffic (ESALs)	Overlay Thickness (in.)
I-12 W	0.207	0.030	24.6	24,399,600	0.0
I-12 E	0.201	0.032	23.7		0.0
LA-28 W	0.788	0.191	9.2	1,512,993	1.4
LA-28 E	0.645	0.275	10.5		1.2
LA-74 W	1.605	0.339	6.7	819,101	2.6
LA-74 E	1.232	0.416	7.0		1.6
LA-44 S	1.115	0.227	5.4	353,256	0.7
LA-44 N	1.005	0.196	6.1		0.6

Note: Temperature-corrected deflection, 1 mil = 0.001 in.

M-E-Based Method. Table 11 presents the overlay design results using the ELMOD5 computer program.

Table 11
Overlay design results using ELMOD 5 method

Project	Average Design Thickness* (in.)	Std.(in.)	Reliability (%)	Overlay Design Thickness (in.)
I-12 W	0.00	0.00	97	0.0
I-12 E	0.00	0.00		0.0
LA-28 W	1.12	1.61	95	2.8
LA-28 E	2.40	3.60		4.0
LA-74 W	5.53	4.09	85	9.8
LA-74 E	3.98	3.50		7.6
LA-44 S	0.09	0.33	85	0.4
LA-44 N	0.04	0.22		0.3

Note: Average overlay thickness over all FWD test points, representing 50% design reliability only.

As shown in Table 11, a variety of overlay thicknesses was obtained. In three projects I-12W, I-12E, and LA-28W, the predicted overlay thicknesses by ELMOD5 were smaller than those obtained from the current LADOTD method. For the other five sections, the ELMOD5 determined thicknesses were higher. For projects LA-74W and LA-74E, the ELMOD5 determined overlay thicknesses were 9.8 in. (248.9 mm) and 7.6 in. (193 mm), respectively. These thicknesses are obviously too high to be believed, so they're not considered as valid values.

Table 12 presents the overlay design results using the EVERPAVE computer program. Similar to ELMOD5, a mixed bag of overlay thicknesses was obtained from the EVERPAVE method.

Table 12
Overlay design results using EVERPAVE 5 method

Project	Backcalculated Moduli (ksi)			Overlay Design Thickness (in.)
	AC	Base	Subgrade	
I-12 W	575	280	25	0.0
I-12 E	620	270	24.5	0.0
LA-28 W	478	143	16.5	2.5
LA-28 E	502	158	17.8	2.0
LA-74 W	435	138	18.2	2.5
LA-74 E	429	110	15.9	1.0
LA-44 S	380	68	17.4	0.5
LA-44 N	378	65	18	0.5

In summary, both the ELMOD 5 and EVERPAVE programs are an M-E based overlay thickness design procedure. Many required design inputs, such as the fatigue and rutting criteria, are not directly available from in-situ NDT tests. Therefore, direct implementation of these design procedures requires further local calibration of those empirical relationships.

Summary on Overlay Design Methods

Figure 8 presents a summary of overlay thickness design results for the four projects considered. The results of I-12 stand out from the others as shown in Figure 8. That is, all NDT-based methods indicated that no overlay was required for the exiting pavement of I-12. However, the current LADOTD method calls for a structural equivalent of 3.4 in. of overlay for I-12. According to the NDT deflection results, the average D1 of the FWD in both I-12 traffic directions was less than 3.1 mils. The condition survey results also indicated that the existing pavement of I-12 has only minor rutting, minor cracking, and low IRI (Table 5). Obviously, another 3.4 in. of structural equivalent overlay thickness on the top of relatively structure-sound existing pavement of I-12 seems not needed. Due to lack of in situ pavement strength test and condition survey, it was found that the current LADOTD method appeared to have under-estimated both existing pavement strength (i.e. SN_{eff}) and subgrade resilient modulus for the I-12 pavement structure, which caused the overdesigned overlay thickness.

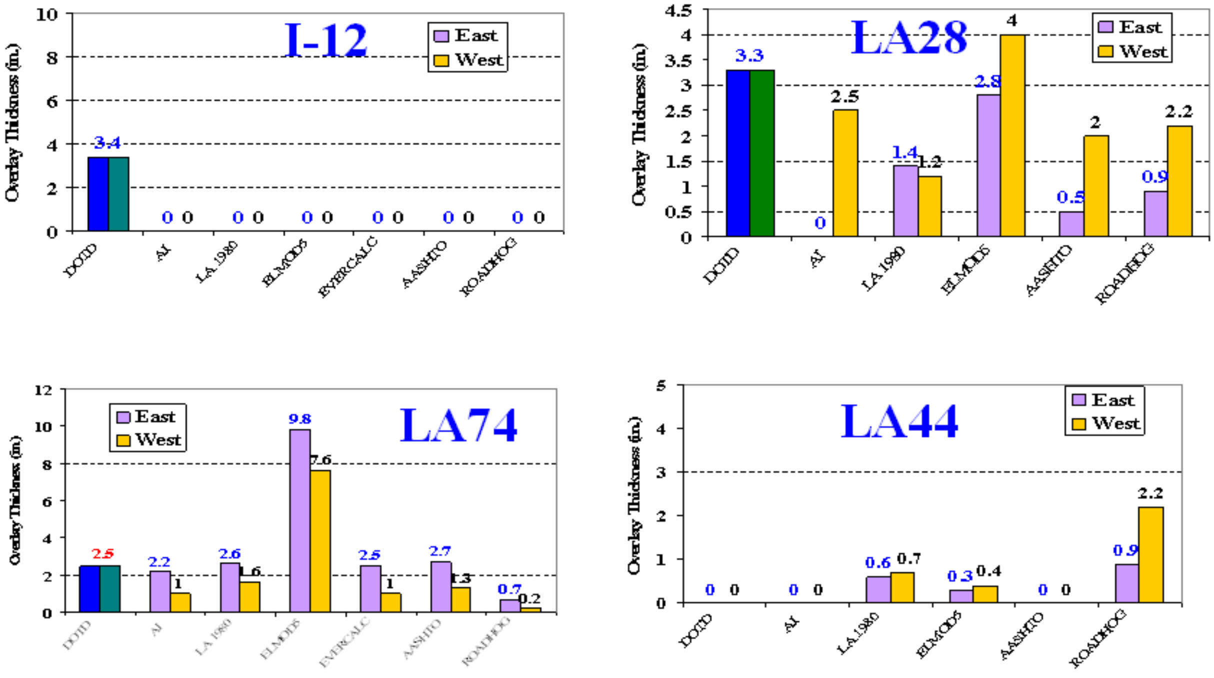


Figure 8
Summary of overlay thickness design results

Figure 8 also indicates that different NDT methods resulted in different sets of overlay thicknesses by using same sets of NDT results. Due to the variation in the existing pavement strengths, all NDT methods called for different overlay thicknesses for different traffic directions. Nevertheless, the current LADOTD method failed to do so because the in-situ pavement conditions for different traffic direction were assumed to be the same in the analysis. On the other hand, without verification and calibrations, none of those NDT methods can be directly used for the Louisiana pavement condition.

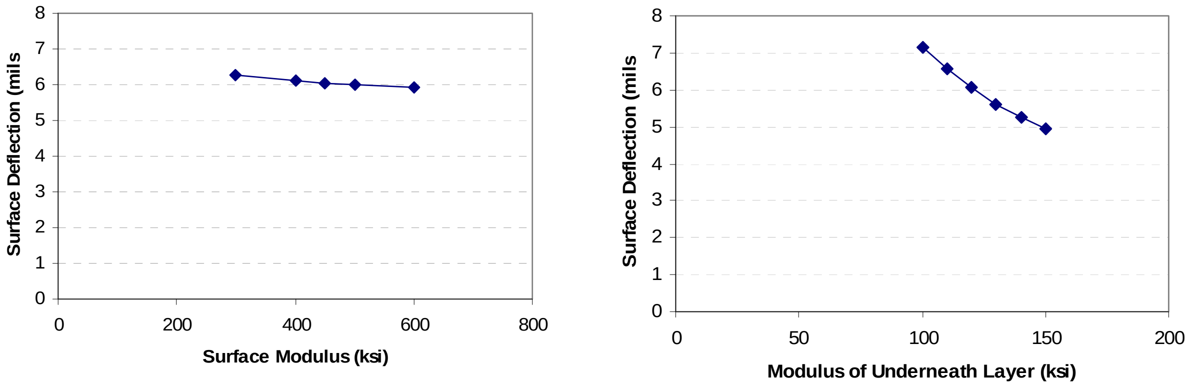
Development of NDT-Based Overlay Design Method for Louisiana Flexible Pavements

LADOTD has begun developing calibration models for implementing the new MEPDG method in Louisiana. The calibrated MEPDG will include an M-E and NDT based overlay design module. Clearly, any effort on local calibration of any of those aforementioned NDT overlay design methods in Louisiana is redundant and beyond the scope of this study. However, the process of local calibration and full implementation of the MEPDG may take many years to accomplish. Therefore, a modified effective thickness (ET) overlay design method was developed in this study based upon testing and research conducted on Louisiana highways. The proposed method may be used prior to the implementation of MEPDG in Louisiana.

Evaluation of Existing Pavement Condition

Evaluation of the existing pavement is a key step in an overlay rehabilitation design. When a pavement's in-situ strength is expressed in terms of SN_{eff}, one should know that the SN_{eff} does not always one-to-one relate to the pavement layer modulus (or moduli). In other words, a layer with a higher modulus does not necessarily possess a greater SN_{eff} than a layer with a lower modulus. For example, a crushed stone base shares a same design layer coefficient (i.e., $a = 0.14$) as a soil cement base. When the two base layers have the same layer thickness, technically they are expected to have equal in-situ structural numbers, even though the soil cement often is known to have a higher in-situ elastic modulus than a crushed stone base.

On the other hand, when NDT deflections are involved in evaluation of the existing pavement, one should aware that the magnitude of pavement surface deflection is largely dependent on the moduli of underneath pavement layers, not top asphalt layers. The sensitivity of different modulus on surface deflections is showed in Figure 9. The computation was based on a two-layer pavement structure under a 9,000-lb. FWD load using ELSYM5, an elastic multi-layer computer analysis program originally developed at the University of California at Berkeley *[32]*. Figure 9a indicates that the surface deflection of an existing pavement does not change significantly as the surface asphalt concrete modulus increases from 300 ksi to 600 ksi. However, it does decrease drastically when the underneath base and subgrade modulus increase from 100 ksi to 150 ksi, as shown in Figure 9b.



(a) **(b)**

Figure 9
Surface maximum deflection under 9,000-lb. FWD load

Most of the existing pavements in Louisiana use base courses such as soil cement, sand shell, or clam shell over a relatively weak subgrade. Those materials have different performance characteristics when compared to a crushed stone base course. A comprehensive pavement evaluation chart (Figure 10) was then developed by Kinchen and Temple to catalogue in-situ pavement strength conditions in Louisiana *[1].* As shown in Figure 10, an effective structural number (SN_{eff}) and a design subgrade modulus of existing pavements can be determined based on a temperature-corrected Dynaflect center deflection and a percent spread value. The percent spread value is calculated by determining the average of five sensor deflections and dividing that by the first sensor deflection multiplied by 100. The determination of the SN value from the Louisiana Pavement Evaluation Chart is hereafter called the “Dynaflect method.”

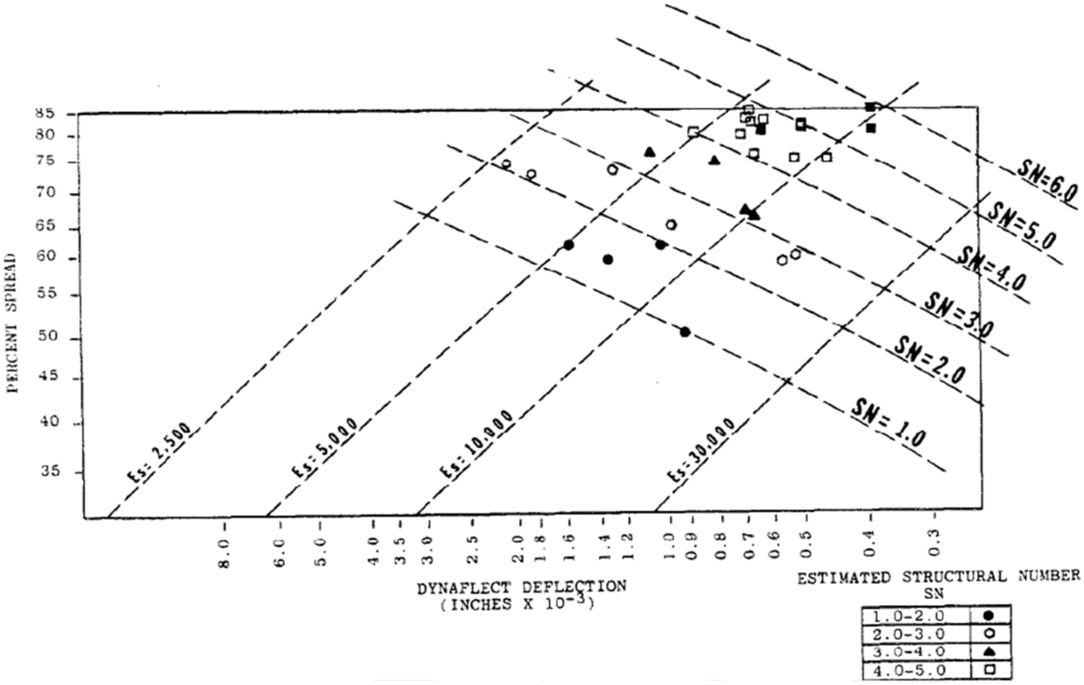
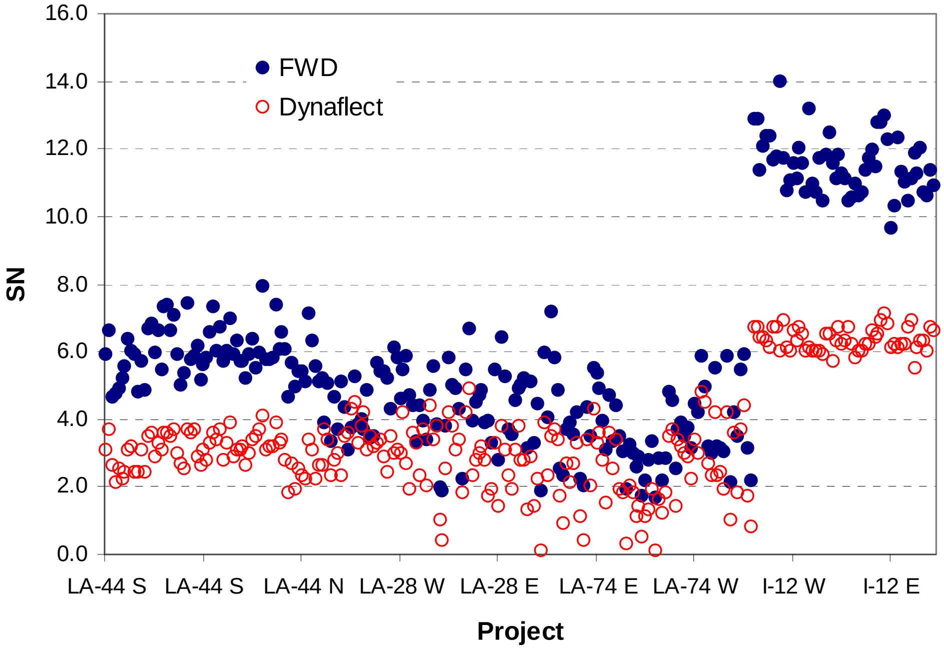
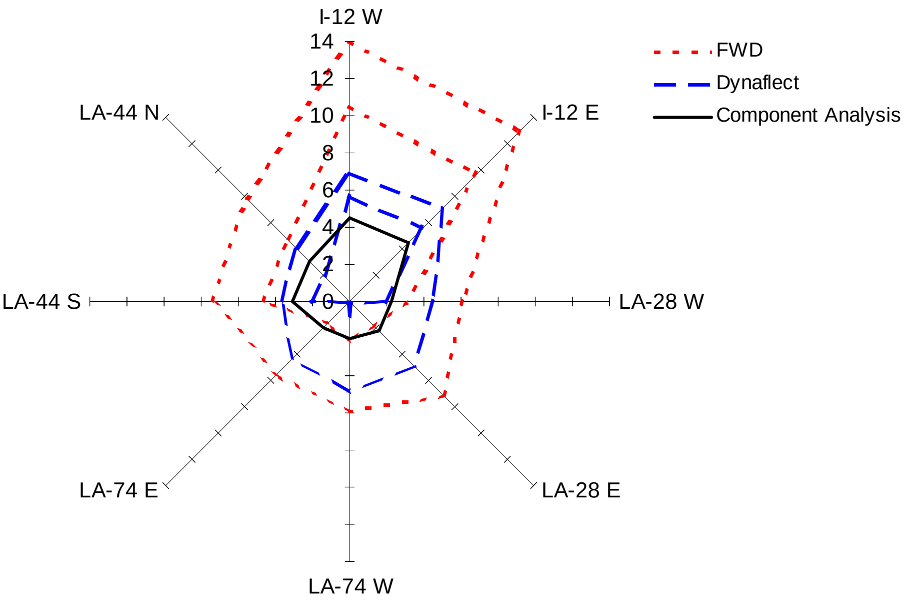


Figure 10
Louisiana pavement evaluation chart *[1]*

The Louisiana Pavement Evaluation Chart shown in Figure 10 was modified from an evaluation chart developed by N.K. Vaswani with an inclusion of a Louisiana Dynaflect-Benkelman beam correlation *[30] [1]*. The SN values in the chart were calibrated using 28 failed asphalt overlay projects *[1]*. The individual SN points in the figure represent in situ estimated SN-values based on field cores. Past research experience indicates that SN_{eff} determined from the Dynaflect method matches reasonably well to the SN-value determined by the LADOTD component analysis method when good engineering judgment is applied. On the other hand, the SN value predicted from the AASHTO NDT method is usually higher than that from the Dynaflect method. Figure 11a presents the predicted SN_{eff} values obtained from FWD and Dynaflect for the four projects evaluated in Phase I of this study. The FWD SN_{eff} values were backcalculated using the 1993 AASHTO NDT procedure; whereas, the Dynaflect SN_{eff} values were determined from the Louisiana Pavement Evaluation Chart. The SN_{eff} values were also estimated based on the LADOTD component analysis method. As shown in Figure 11a, the SN_{eff} values obtained from FWD were significantly higher than those values obtained from Dynaflect, especially for the I-12 project. On the other hand, as shown in Figure 11b, the Dynaflect SN_{eff} values were observed to be very close (but mostly slightly higher) to those determined from the component analysis method. Overall, the above analysis further confirmed that Dynaflect determined SN values reflect in-situ pavement conditions in Louisiana.



(a) SN$_{eff}$ obtained from FWD and Dynaflect



(b) SN$_{eff}$ ranges from FWD, Dynaflect and condition survey

Figure 11

Effective structural number obtained from FWD and Dynaflect

Since the development of the Louisiana Pavement Evaluation Chart was pure empirically based (i.e., it was modified through inclusion of an empirical correlation between Dynaflect and Benkelman deflections into the original Vaswani's chart), its theoretical base needs to be further validated. The following analysis based on the multi-layer elastic theory may be served as a validation for theoretical soundness of the developed Louisiana Pavement Evaluation Chart.

The Dynaflect loading device was modeled using two pressure loads, each of 500 lb. The geometric configuration of the Dynaflect test was measured as shown in Figure 12. Based on the Dynaflect test loading, surface deflections (W1-W5) of a two-layer pavement structure can be computed using ELSYM5, a computer program originally developed at the University of California at Berkeley. By varying moduli for both the AC layer and subgrade, a theoretical chart of SN vs. M_r was developed, as shown in Figure 13(a). The derived theoretical chart was then overlapped with the Louisiana Pavement Evaluation Chart, Figure 13(b). It was found that the Louisiana Pavement Evaluation Chart generally shifts to the right of the theoretic chart. Under the same set of deflections and percent spread, the Louisiana Pavement Evaluation Chart yields a smaller value of SN than the theoretic chart. The results shown in Figure 13b prove that the Louisiana Pavement Evaluation Chart is theoretically sound. In addition, it also explains why the AASHTO NDT method determined that SN values are always higher than Dynaflect SN values as shown in Figure 11a; however, the AASHTO NDT method has not been calibrated to Louisiana pavement conditions.

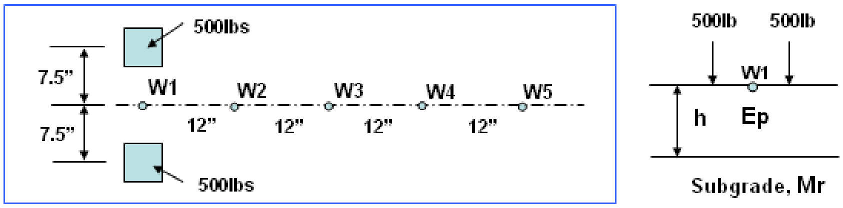
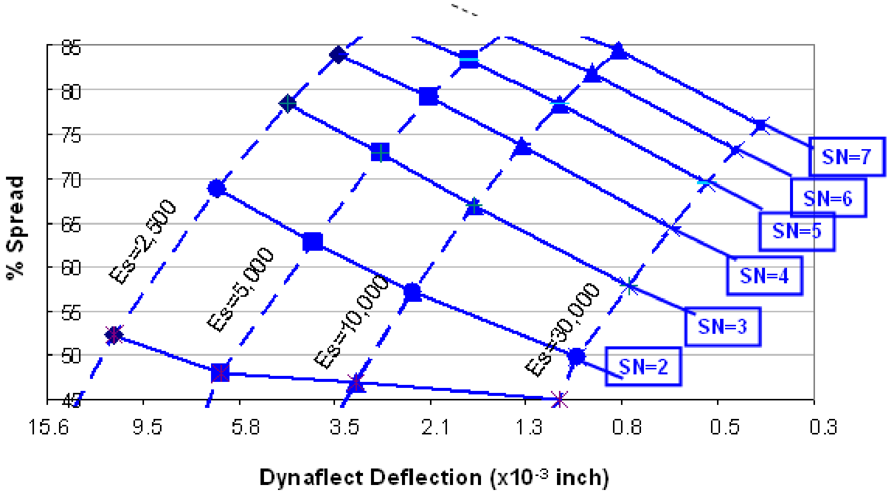
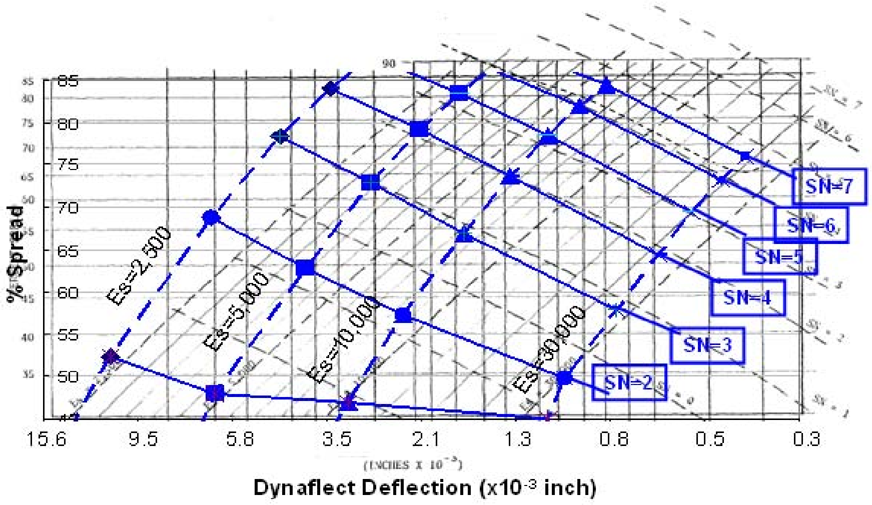


Figure 12
Evaluation of Dynaflect deflections



(a)



(b)

Figure 13
Theoretical evidence of Louisiana pavement evaluation chart

Proposed NDT-Based Overlay Design Method

The proposed overlay thickness design method generally follows similar design steps as described in the 1993 AASHTO NDT-based overlay design procedure *[7]*. Specifically, the following steps are involved:

Step 1: Information on existing pavement design and construction.

- Determine thickness and material type of each pavement layer
- Collect available subgrade soil information

Step 2: Traffic analysis.

- Predict future 18-kip ESALs in the design lane over the design period.

Step 3: Deflection testing.

- Perform FWD deflection measurements at 0.1-mile intervals along project's mile post on the existing pavement surface.

Step 4: Determination of Design SN_{eff}

- Compute $SN_{eff\,|(FWD)}$ using the 1993 AASHTO NDT method, as described in this report with equations (13), (14) and (15)
- Determine the design SN_{eff} using the following equation:

$$Design\ SN_{eff} = 2.58 * Ln(SN_{eff|(FWD)}) - 0.77 \tag{18}$$

Step 5: Determination of required structural number for future traffic (SN_f).

- Determination of design Mr for subgrade

  The design M_r value is computed using the following equation:

$$Design\quad Mr = 0.4 \times \left(\frac{0.24P}{d_r r}\right) \tag{19}$$

  where, P = applied FWD load of approximately 9,000 lb. (40 kN),
  d_r = deflection at a distance of 36 in. (900 mm) from the center of the load, and
  r = 36 in. (900 mm).

- Design PSI loss

  PSI immediately after overlay (P1) minus PSI at time of next rehabilitation (P2). Note that P1 and P2 should be selected based on the current LADOTD overlay design method.

- Overlay design reliability R (percent).

  R value should be selected based on the current LADOTD overlay design method.

- Overall standard deviation S_o for flexible pavement.

  S_o value should be selected based on the current LADOTD overlay design method.

- Compute SN_f for the above design inputs using the 1993 AASHTO flexible pavement design equation *[7]*.

Step 6: Determination of overlay thickness.

- The design thickness of AC overlay is computed as follows:

$$h_{OL} = \frac{SN_{OL}}{a_{OL}} = \frac{SN_f - SN_{eff}}{0.44}$$

where, h_{OL} = required thickness of asphalt overlay,
SN_{OL} = required structural number of asphalt overlay,
a_{OL} = structural layer coefficient of asphalt overlay,
SN_f = structural number required to carry future traffic, and
SN_{eff} = design effective structural number determined from equation (18).

It should be noted that equation (18) was developed based on 271 FWD-Dynaflect paired data points (i.e., FWD and Dynaflect tested on a same location one after the other) on 13 in-situ asphalt pavements previously tested by LTRC. As shown in Figure 14, a fairly good correlation is existed between FWD and Dynaflect determined SN values with a R^2-value of 0.92. The significance for developing such a correlation equation lies in that it can correctly adjust over-estimated SN_{eff} values obtained from the 1993 AASHTO NDT procedure into Louisiana pavement condition based, Dynaflect deflection estimated SN values. Therefore, equation (18) is recommended use in the currently proposed overlay thickness design. Certainly, when more test data are available, this relationship can be further refined.

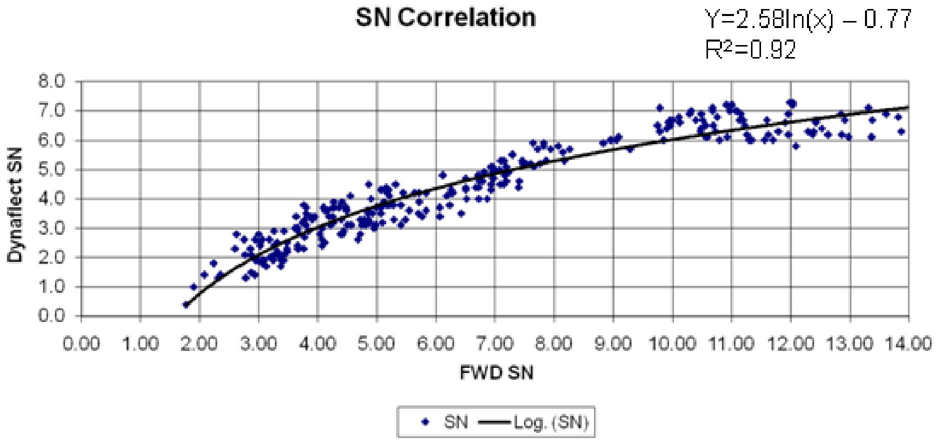


Figure 14
Correlation between SN_{FWD} and $SN_{Dynaflect}$

On the other hand, equation (19) was modified from research results obtained from a previous "Subgrade Modulus" study at LTRC *[31],* in which a design subgrade modulus (M_r) was found linearly related to an FWD backcalculated subgrade modulus with a correlation coefficient of 0.42. More details may be referred to elsewhere *[31]*. To simplify the computation effort without significantly reducing the accuracy of the prediction, equation. (19) was thus developed based on the direct use of an FWD 36-inch sensor deflection value. The equation (19) predicted modulus values were then compared with those determined from the laboratory resilient modulus test results; the two sets of M_r values matched reasonably well.

Overlay Design using the Proposed NDT Method

The aforementioned overlay thickness design procedure proposed for the structural overlay design for Louisiana flexible pavements has been implemented in a windows-based computer program for fast data processing. More details of this design computer program are presented in the Appendix of this report.

Table 13 presents the overlay design results from the proposed overlay design method (i.e., using the developed computer program) as compared to those obtained from the 1993 AASHTO procedure. As shown in Table 13, both methods indicate that no overlay thickness was required by projects I-12 and LA 44. On the other hand, for projects requiring the structural overlay, the thicknesses determined from the proposed method were quite different than those from the 1993 AASHTO procedure.

Table 13
Overlay design results using 1993 AASHTO and proposed methods

Project	SN_{eff} (in.)		SN_f (in.)	Overlay Design Thickness (in.)	
	FWD	Proposed		AASHTO	Proposed
I-12 W	11.65	5.56	4.77	0.0	0.0
I-12 E	11.31	5.49	4.84	0.0	0.0
LA-28 W	4.14	2.89	4.34	0.5	3.3
LA-28 E	3.5	2.46	4.39	2.0	4.4
LA-74 W	3.24	2.26	3.8	1.3	3.5
LA-74 E	2.84	1.92	4.02	2.7	4.8
LA-44 S	5.74	3.74	3.59	0.0	0.0
LA-44 N	5.8	3.77	3.5	0.0	0.0

Figure 15 presents the overlay thickness design results from both proposed and current LADOTD overlay design methods. Compared to the proposed method, the current LADOTD method generally overestimates the overlay thickness for project I-12, and underestimates the thicknesses for projects LA-28E, LA-74W, and LA74E.

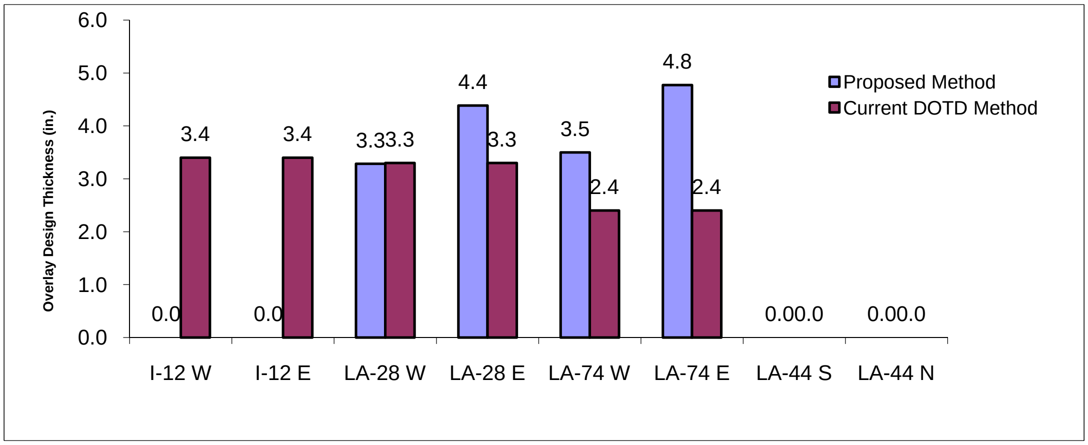


Figure 15
Overlay design results of proposed method and current LADOTD method

It is noted that previously determined overlay thicknesses are structural overlay thicknesses based on the structural deficiency of the existing pavement for future traffic. Functional overlay is not included in the design. Based on field condition survey results (Figure 5 and Table 5), no structural overlay required for both I-12 projects is deemed valid based on the current roadway condition, but the routine maintenance repair is still needed for localized distresses such as cracking and rutting. However, for project LA-44, a functional overlay appears to be needed urgently due to high IRI values. On the other hand, for under-estimated sections, such as LA-74E, an under-designed overlay thickness will result in an early pavement failure. Because the current LADOTD method could not reflect the in-situ pavement condition, it is thought to have underestimated the structural overlay thickness for projects LA-28E, LA-74W, and LA-74-E.

Overlay Design Using MEPDG Version 1.0

Table 14 presents analysis results obtained from the MEPDG Version 1.0 using the default Level 3 input values. As shown in the table, for projects I-12W and I-12E, the overlay thicknesses determined by both the proposed and current LADOTD methods failed due to not meeting the asphalt concrete (AC) permanent deformation criteria. In these two cases, the AC permanent deformation criteria still could not be met even using an overlay thickness of 10 in. (254 mm). This indicates that an overlay design cannot be performed by the MEPDG software with default values. More research is warranted to calibrate the MEPDG distress models as well as to determine the required overlay design input values.

Table 14
Results of overlay thickness verification using MEPDG software

Project	Overlay thickness (in.)		MEPDG verified results	
	LADOTD	Proposed	LADOTD	Proposed
I-12W	3.4	1*	AC Permanent Deformation Fail	AC Permanent Deformation Fail
I-12E	3.4	1*	AC Permanent Deformation Fail	AC Permanent Deformation Fail
LA-28W	3.3	3.3	AC Permanent Deformation Fail	AC Permanent Deformation Fail
LA-28E	3.3	4.4	AC Permanent Deformation Fail	Pass
LA-74W	2.4	3.5	Pass	Pass
LA-74E	2.4	4.8	Pass	Pass
LA-44S	1*	1*	Pass	Pass
LA-44N	1*	1*	Pass	Pass

Note: * The design thickness was zero. However, 1.0 inch was selected as it is the minimum overlay thickness required in a MEPDG overlay thickness design.

Analysis of Phase II Projects

The proposed overlay design method was used to design the required overlay thickness for Phase II projects. The design results were compared to the thickness results obtained from the current LADOTD method. Figure 16 presents the comparison (thickness difference obtained between the current LADOTD method and the proposed method) between two sets of overlay design thicknesses. It is noted that a positive thickness value in Figure 16 indicates an over-designed asphalt concrete overlay thickness by the current LADOTD method; whereas, a negative value stands for an under-designed thickness. Among the 11 projects evaluated, about half were considered under-designed; the under-designed overlay thicknesses ranged from 0.2 in. to 1.6 in. Another half of considered projects were over-designed. The corresponding overdesigned asphalt concrete thicknesses varied from 0.3 in. to 1.7 in. (Figure 16).

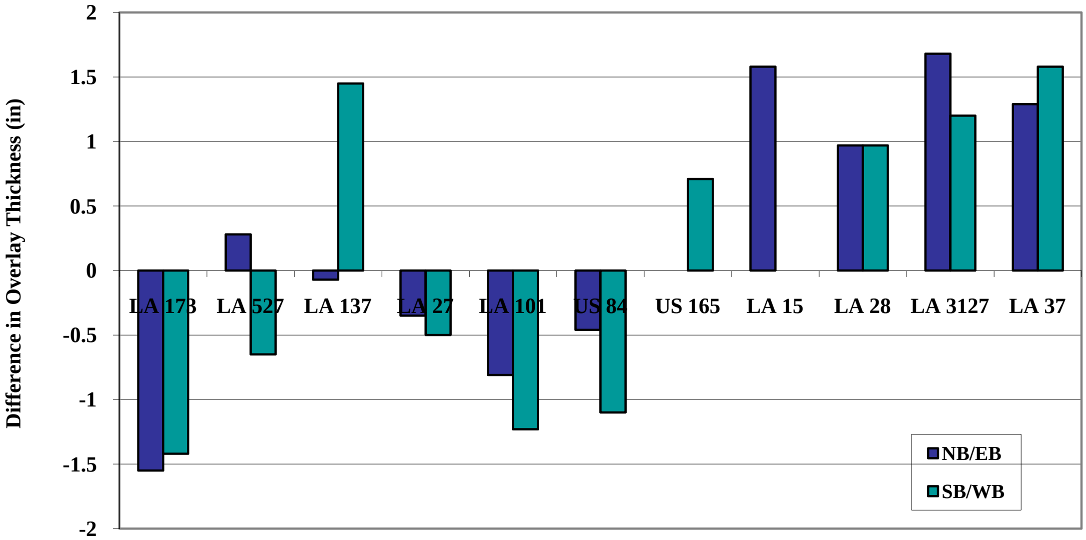


Figure 16
Comparison of overlay thickness

Cost/Benefit Analysis

The cost/benefit analysis was performed on all projects evaluated in this study, including 4 Phase I projects and 11 Phase II projects. For over-designed projects (i.e., those positive thickness values in Figure 16), the direct benefit of using the proposed overlay design method would be construction cost savings. Assuming that the construction cost for asphalt overlay is $80 per ton, construction cost savings were computed based on cost differences between overlay plans obtained from the LADOTD overlay method and the proposed overlay design method in this study. For instance, construction costs of two overlay thickness design alternatives in I-12 project are listed in Table 15. Since the current LADOTD plan calls for 2 in. milling and 4.5 in. overlay, the proposed method would call for 2 in. milling and 2 in. inlaying only for pavement functional repairing. As shown in Table 15, the total cost savings would be $3,265,180 for a 10.5-mile long I-12 evaluated project. It is noted that in the cost comparison, costs of the milling operation should not be considered because the same expenses are applied in both alternatives. For a four-lane highway like I-12 (with 12-ft wide lanes), a 1-in. less overlay thickness will potentially save $123,900 per mile in construction.

Table 15
Comparison of initial construction costs in I-12

Alternatives	Length (miles)	Unit Prices ($)	Quantity (ton)	Construction Costs ($)
A: LADOTD Plan (2" mill/4.5" overlay)	10.541	80 per ton	73,467	5,877,324
B: Proposed Method (2" mill/2" overlay)	10.541	80 per ton	32,652	2,612,144
Total Construction Cost Savings (A – B)				$3,265,180

The construction cost savings for all over-designed projects in this study are listed in Table 16. By adding all the miles on all over-design projects, the total potential construction cost savings for the 15 project sections (103 total miles) would be $6,409,658.

For under-designed overlay rehabilitation projects, the after-overlay pavement performance would be adversely affected by a thinner asphalt concrete overlay. For instance, as shown in Figure 17, for a 1-in. under-designed thickness on the LA74 project, the computed pavement life would be 4.1 years, not 10 years as required by the overlay thickness design. The pavement life was computed according to the design future traffic (ESALs) and the NDT determined SNeff. At the end of 4.1 years of service, LA74 would require another overlay in order to bring the pavement back to the required PSI value of 4.0 (Figure 17).

Table 16
Analysis of cost saving for over-designed projects

Project No.	Route	Length Miles	DOTD Plan	Proposed	Difference	Quantity (ton)	Cost Savings ($)
			Overlay(in.) +mill (in.)	Overlay (in.) +mill (in.)	AC Thickness (in.)		
1	LA 527NB	3.788	2+1	1.7+1	0.3	411	32,854
2	LA 137	7.11	2.75+2	1.3+1	1.45	3992	319,347
3	US 165	7.311	0.75"AC	0.0	0.75	2010	160,791
4	LA 15	5.46	2.75+2	1.2+2	1.6	3340	267,224
5	LA28EB	7.293	2+1.75	1.0+1.75	1.0	2739	219,131
6	LA 28WB	7.293	2+1.75	1.0+1.75	1.0	2739	219,131
7	LA 3127N	5.58	3.5+2	1.8+2	1.7	3630	290,381
8	LA 3127S	5.58	3.5+2	2.3+2	1.2	2593	207,415
9	LA 37N	5.44	3.5+1.5	2.2+1.5	1.3	2717	217,377
10	LA 37S	5.44	3.5+1.5	1.9+1.5	1.6	3328	266,245
11	LA 28	6.7	4.5+2	4+2	0.5	1297	103,770
12	LA 44EB	7.54	3.5+2	1.6+2	1.9	5547	443,762
13	LA 44WB	7.54	3.5+2	1.8+2	1.7	4963	397,050
14	I-12EB	10.541	4.5+2	2+2	2.5	20407	1,632,590
15	I-12WB	10.541	4.5+2	2+2	2.5	20407	1,632,590
Total		103.157					6,409,658

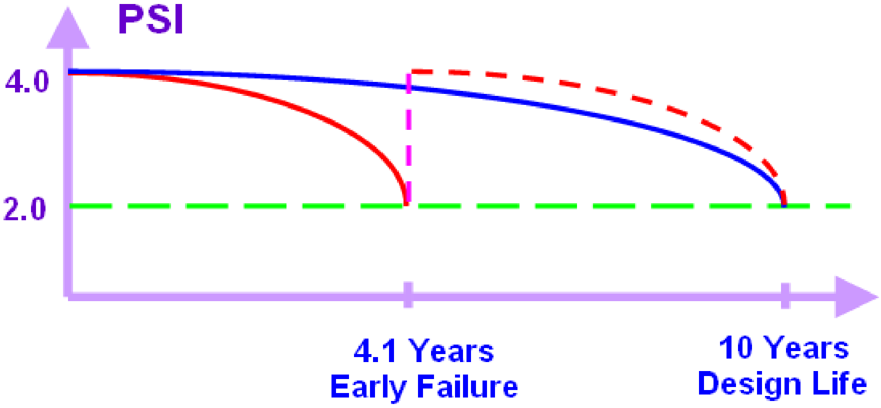


Figure 17
Performance of under-designed overlay thickness on LA74

To evaluate potential cost benefits of using an overlay thickness determined from the proposed method in lieu of an under-designed overlay thickness by the current LADOTD method, a life cycle cost analysis (LCCA) was performed in this study. It is assumed that an action of 2-in. milling and 2-in. overlay is necessary to bring a pavement back to its psi value of 4.0, when an under-designed asphalt concrete overlay reaches its prematured pavement life before a 10-year pavement design life (Figure 18). For a given project in the LCCA, Alternative A is for the estimation of construction costs of an asphalt concrete overlay using the proposed overlay thickness; whereas, Alternative B is for the cost analysis including an overlay with a thickness determined by the LADOTD method, an action of 2-in. milling and 2-in. overlay and a residual pavement value at the end of a 10-year pavement design life. A positive cost difference of the two alternatives (A and B) is deemed the cost benefit of using the proposed method in an overlay design. Note that a discount rate of 5 percent and a present worth cost are used in the LCCA. Table 17 presents the cost savings of all under-designed projects investigated in this study. After adding the mileages of all under-designed projects, the total potential savings in the present worth cost would be $2,537,246 per lane for an 80-mile long pavement.

Table 17
Life cycle cost analysis of cost saving for under-designed projects

Project #	**Route #**	**Length (miles)**	**LADOTD Design Plan**	**Under-designed Difference**	**Pavement Life (years)**	**Total Saving ($)**
			overlay + mill			
1	LA 173	6.416	3.5+0.5	-0.6	5.6	241,864
2	LA 173	6.416	3.5+0.5	-0.4	6.5	245,739
3	LA 527	3.788	2+1	-0.7	6.3	120,978
4	LA 27	16.96	2.5+2	-0.4	8.7	544,454
5	LA 27	16.96	2.5+2	-0.5	6.8	588,206
6	LA 101	3.115	4+3	-0.8	6.3	84,046
7	LA 101	3.115	4+3	-1.2	4.3	67,214
8	US 84	8.004	2.5+0	-0.5	7.8	257,071
9	US 84	8.004	2.5+0	-1.1	4.8	189,717
10	LA 74	3.35	3.5+2	-0.9	5.7	88,691
11	LA 74	3.35	3.5+2	-2.3	2.8	10,926
Total		79.478				2,537,246

Cost of Performing FWD Tests

Tables 16 and 17 presented the cost savings associated with using the proposed procedure but did not include the cost of performing FWD testing. If the new procedure was adopted by LADOTD, FWD testing would be conducted by consultant contracts, and a package of several projects would be the most feasible way to perform the work. Cost estimates were solicited from industries for performing FWD tests for the following scope and tasks:

- 10 projects (located throughout the state)
- 5 miles total length per project
- Testing interval (0.1 mile each direction)
- Asphaltic concrete roadway
- Report, data base, and data analysis
- LADOTD provides typical section data such as pavement layer(s) and base course thicknesses.

The estimated cost would be approximately $79,430 total to perform testing and to provide a report for 50 miles of roadway. Table 3 shows there were approximately 117.71 miles of roadway assessed in this project. This means that the FWD testing would cost approximately $187,006.81 ($79, 430 * (117.31 / 50) = $187, 006.81) for the projects listed in Table 3.

Therefore, the overall cost savings for this project would be $8,759,897 [$6,409,658 (Table 16) + $2,537,246 (Table 17) – $187, 007 (FWD costs)]. This translates into a savings of $74,419 per mile.

CONCLUSIONS

Fifteen overlay rehabilitation projects with different traffic levels and design requirements were selected for the analysis in this study. Five NDT-based plus 1980 Louisiana Dynaflect-based overlay design methods were investigated and used in the Phase I analysis of designing required overlay thicknesses. A modified NDT-based overlay thickness design method has been developed for selecting the asphalt concrete overlay thickness required to structurally rehabilitate flexible pavements in Louisiana. This method together with a developed computer program is recommended to be used by LADOTD before its full implementation of the new M-E pavement design method. Some specific observations and conclusions may be drawn from this study:

- Results indicated that the 1993 AASHTO NDT procedure generally over-estimated the effective structural number for the existing flexible pavements in Louisiana, which would result in an under-designed overlay thickness.
- Without local calibration, none of the five selected NDT-based overlay design methods could be directly implemented in Louisiana since none of them would represent the actual Louisiana pavement conditions. On the other hand, the 1980 Louisiana overlay design method is also deemed not implementable due to its out-of-date overlay thickness design charts based upon Dynaflect-measured deflections.
- The Louisiana Pavement Evaluation Chart, originally developed by Kinchen and Temple, has been proved not only applicable to the Louisiana flexible pavement conditions, but also based on the elastic-layered pavement theory. Therefore, it is recommended to be further used in the evaluation of existing pavement strengths of Louisiana flexible pavements.
- A strong correlation between FWD and Dynaflect determined structural numbers was obtained in this study. Such a correlation is quite useful because it builds a link between the layered elastic theory applied in a flexible pavement structure and Louisiana in-situ pavement conditions.
- The LCCA analysis indicates that, in lieu of the current LADOTD overlay design method, a significant amount of cost savings ($74,419 per mile) would be obtained for both over- and under-designed pavements when applying the proposed NDT-based overlay design method developed in this study.

RECOMMENDATIONS

Evidence exists from this study that a cost savings would be realized by utilizing the proposed overlay design procedure. In order to further validate the findings in this study, two things should occur. First, additional projects should be sampled to fortify the findings, and the proposed overlay design procedure should be used on selected projects and monitored for performance.

It is envisioned that the modified overlay thickness design method presented in this study would be a replacement for the current LADOTD component analysis overlay design method and it would be used only in the structural overlay thickness design of flexible pavements in Louisiana. For those roads, such as low volume roads that have a higher probability of requiring functional instead of structural overlays, this proposed overlay design process would be of little use except to validate that a structural overlay is not required.

ACRONYMS, ABBREVIATIONS, & SYMBOLS

AASHTO	American Association of Highway and Transportation Officials
AC	Asphalt Concrete
DGAC	Dense-Graded Asphalt Concrete
DOT	Department of Transportation
Dynaflect	Dynamic Deflection Determination System
D1	Deflection Measured at Center of FWD Plate
D9	Deflection Measured at 72 inches from Center of FWD Plate
D_{80}	80th percentile of the deflections at the surface for a test section in inches
ESAL	Equivalent Single Axle Load
ET	Effective Thickness
FWD	Falling Weight Deflectometer
GE	Gravel Equivalent
Gf	Gravel Factor
IRI	International Roughness Index
LADOTD	Louisiana Department of Transportation and Development
LCCA	Life Cycle Cost Analysis
LTRC	Louisiana Transportation Research Center
MEPDG	Mechanistic-Empirical Pavement Design Guide
M_r	Resilient Modulus of Soil Subgrade
NDT	Non Destructive Testing
PRD	Percent Reduction in Deflection
RRD	Representative Rebound Deflection
SN	Structural Number
SN_{eff}	Effective Structural Number of an Existing Pavement
SN_f	Future Required Structural Number of an Overlaid Pavement
TDS	Tolerable Deflection at the Surface
TI	Traffic Index

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APPENDIX

LTRC Overlay Design Program User's Manual

The LTRC Overlay Design Program (LTRC-ODP) was developed in the Visual Basic environment. This document provides overlay main procedures, design flowchart, and information related to running the LTRC-ODP. For other detailed design concepts, refer to Final Report 06-2P. This document does not contain detailed instructions regarding the normal file operations associated with the Windows operating environment. Microsoft Office Excel 2007 version is needed to view the overlay design results.

1. Main Procedures of LTRC-ODP

The main design procedures of LTRC-ODP contain:

1.1. Importing an FWD File

Import the FWD file; select load level near to 9000 lb., and convert the deflections to 9000 lb. by equation:

$$D_{\mathrm{mod}} = \frac{D_{ori}}{F} \times 9000 \tag{1}$$

where,

D_{mod} = Modified FWD deflections, mills;
D_{ori} = Original FWD deflections, mills; and
F = Load of FWD test, lbf.

1.2. Temperature Calibration

Input the station mid-depth temperature of HMA layer ($^{\circ}$F), Total Asphalt Thickness (in) and Total Pavement Thickness (in). If temperature data have already the FWD file, read these data from the FWD file. For thickness data, at least two stations data are needed. If some stations don't have measured values, calculate the interpolation or extrapolation values.

Select Base Type from "Granular or Asphalt-Treated Base" or "Cement or Pozzolanic-Treated Base" selections.

Determine the temperature calibration coefficient (K). The calculation equations of K with asphalt thickness 2, 4, 8, 12 in. are derived from Figures 5.6 and 5.7 in *AASHTO Guide for*

Design of Pavement Structures 1993. For other asphalt thickness, use interpolation or extrapolation methods to get the K value.

Calculate the temperature calibrated deflection at the center of the load plate (D_{0_cal}), mills:

$$D_{0\_cal} = D_0 \times K \tag{2}$$

where,

D_0 = deflection at the center of the load plate, mills; and

K = temperature calibration coefficient.

1.3. Create SN_{eff}

Calculate the subgrade resilient modulus (M_R) by equation:

$$M_R = \frac{0.24 * P}{\frac{dr}{1000} \times r} \tag{3}$$

where,

P = 9000 lb.;

dr = Deflection at a distance r = 36 in from the center of the load, mills; and

r = 36 inches.

Calculate the effective modulus of the pavement (E_p) from the following equation:

$$\frac{D_{0\_cal}}{1000} = 1.5 \times p \times a \times \left\{ \frac{1}{M_R \sqrt{1 + \left(\frac{D_T}{a} \sqrt[3]{\frac{E_p}{M_R}} \right)^2}} + \frac{\left[1 - \frac{1}{\sqrt{1 + \left(\frac{D_T}{a} \right)^2}} \right]}{E_P} \right\} \tag{4}$$

where,

D_{0_cal} = calibrated deflection at the center of the load plate, mills;

P = NDT load plate pressure, psi, here is 82.3 psi;

a = NDT load plate radius, in., here is 5.9 in.;
D_T = Total thickness of pavement layers above the subgrade, in.;
M_R = Subgrade resilient modulus, psi; and
Ep = Effective modulus of all pavement layers above the subgrade, psi.

Calculate the effective structural number direct from FWD (SN_{eff_FWD}) by the equation:

$$SN_{eff\_FWD} = 0.0045 \times D_T \times \sqrt[3]{E_p} \tag{5}$$

Calculated modified the effective structural number (SN_{eff}) by equation:

$$SN_{eff} = 2.58 \times LN(SN_{eff\_FWD}) - 0.77 \tag{6}$$

1.4. Create SN_f

Calculate the design subgrade resilient modulus (M_{R_Des}), psi, by:

$$M_{R\_Des} = 0.4 \times M_R \tag{7}$$

Input traffic data ESAL (W_{18}); design psi loss (ΔPSI); overlay design reliability (R), %, and Overlay standard deviation (S_0). Calculate the required structural number for future traffic (SN_f) by:

$$\log_{10}(W_{18}) = Z_R \times S_0 + 9.36 \times \log_{10}(SN_f + 1) - 0.20 + \frac{\log_{10}\left[\frac{\Delta PSI}{4.2 - 1.5}\right]}{0.40 + \frac{1094}{(SN_f + 1)^{5.19}}} \tag{8}$$

$$+ 2.32 \times \log_{10}(M_{R\_Des}) - 8.07$$

where,

W_{18} = number of 18-kip ESAL,
Z_R = standard Normal Deviate,
S_0 = overlay standard deviation, and
ΔPSI = design psi Loss.

1.5. Overlay Design

Input Structural Layer Coefficient of Asphalt Overlay (a_{OL}), Milling Thickness (inches), and Structural Layer Coefficient of Milled AC (a_{Mil}).Calculate the overlay design thickness by equation:

$$h_{OL} = \frac{SN_f - \left(SN_{eff} - D_{Mil} \times \alpha_{Mil}\right)}{a_{OL}} \tag{9}$$

where,

h_{OL} = required thickness of asphalt overlay, inches;

SN_f = required structural number for future traffic;

SN_{eff} = modified effective structural number;

D_{mil} = milling thickness (in.);

A_{Mil} = structural layer coefficient of milled AC; and

a_{OL} = structural layer coefficient of new asphalt overlay.

Output the results of required thickness of asphalt overlay: average and standard deviation values.

2. LTRC-ODP Flowchart

The flowchart of LTRC-ODP is shown as:

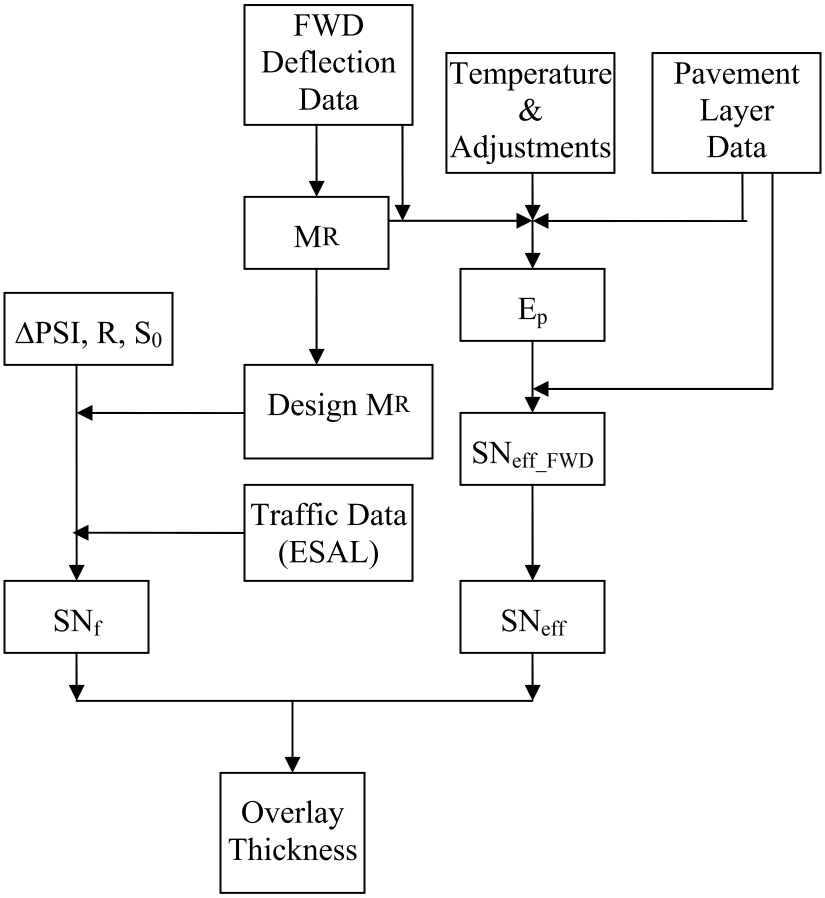
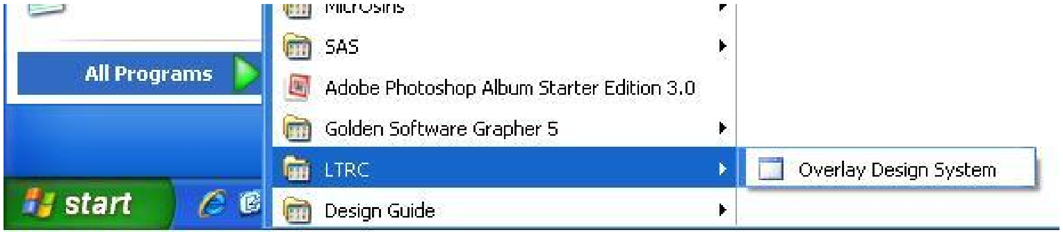


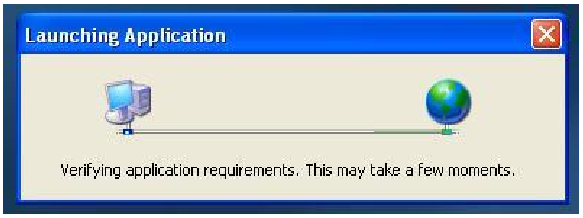
Figure A1
LTRC-ODP flowchart

3. Running the LTRC-ODP

3.1. Start LTRC-ODP

- Click on the Windows Start
- Highlight All Programs→ LTRC→ Overlay Design System, and click once.
- 

- The software will verify Launching Application.



Verifying application requirements. This may take a few moments.

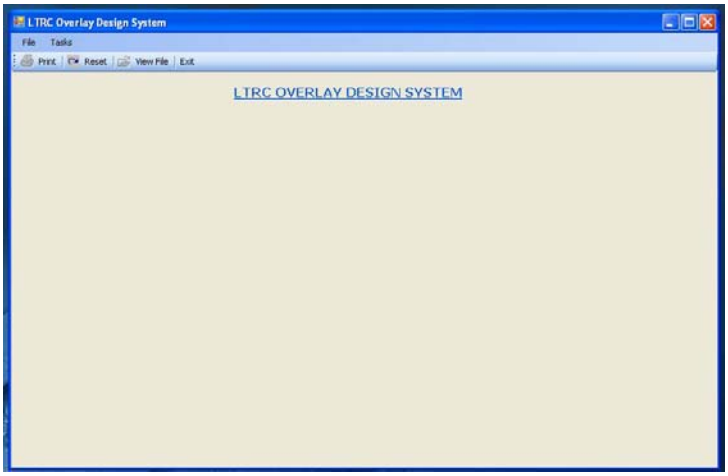
- An interface “LTRC Overlay Design System Application Version 1.0” will appear.

LTRC OVERLAY DESIGN SYSTEM Application

Version 1.0

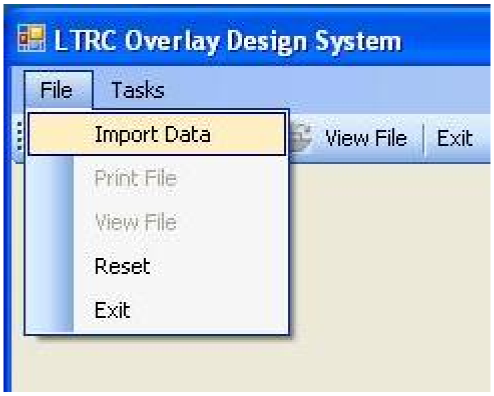
Louisiana Transportation Research Center

- Then the main interface of LTRC-ODP opens.

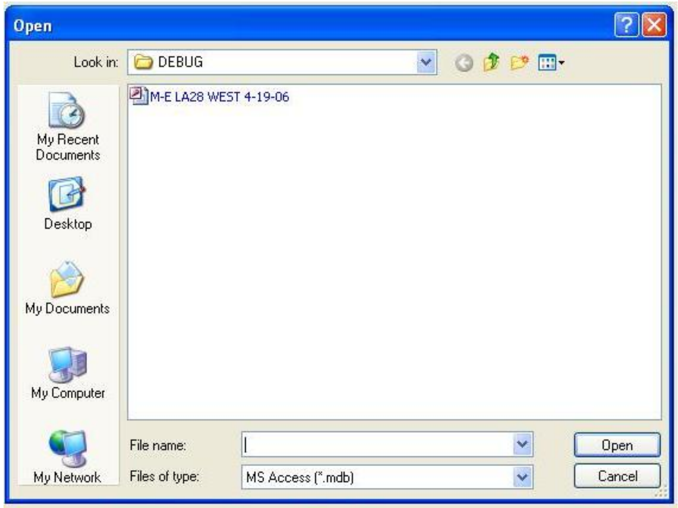


3.2. Importing an FWD File into LTRC-ODP

- Click on “File” in the LTRC-ODP main interface.
- Click the “Import Data” in the File pull-down menu.



- Select the desired FWD file within the “Open” dialog box.
- Once a file has been selected, click “Open” to acknowledge the selection.



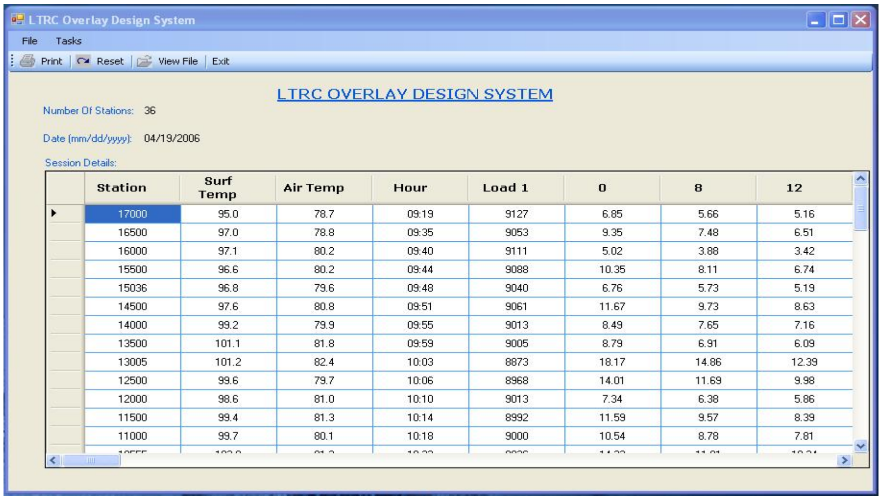
Look in: DEBUG

M-E LA28 WEST 4-19-06

File name:

Files of type: MS Access (*.mdb)

- LTRC-ODP reads the fields FWD file into the software.



Number Of Stations: 36

Date (mm/dd/yyyy): 04/19/2006

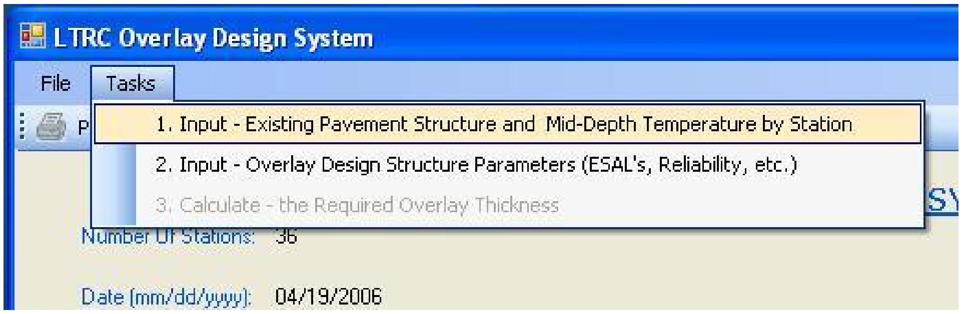
Session Details:

Station	Surf Temp	Air Temp	Hour	Load 1	0	8	12
17000	95.0	78.7	09:19	9127	6.85	5.66	5.16
16500	97.0	78.8	09:35	9053	9.35	7.48	6.51
16000	97.1	80.2	09:40	9111	5.02	3.88	3.42
15500	96.6	80.2	09:44	9088	10.35	8.11	6.74
15036	96.8	79.6	09:48	9040	6.76	5.73	5.19
14500	97.6	80.8	09:51	9061	11.67	9.73	8.63
14000	99.2	79.9	09:55	9013	8.49	7.65	7.16
13500	101.1	81.8	09:59	9005	8.79	6.91	6.09
13005	101.2	82.4	10:03	8873	18.17	14.86	12.39
12500	99.6	79.7	10:06	8968	14.01	11.69	9.98
12000	98.6	81.0	10:10	9013	7.34	6.38	5.86
11500	99.4	81.3	10:14	8992	11.59	9.57	8.39
11000	99.7	80.1	10:18	9000	10.54	8.78	7.81

Note: If the “Reset” entry in the File pull-down menu is highlighted and clicked, imported FWD data will be cleared and returned to original main interface.

3.3. Input Existing Pavement Structure and Mid-Depth Temperature by Station

- Click on "Tasks" in the LTRC-ODP main interface.
- Highlight and click "1. Input-Existing Pavement Structure and Mid-Depth Temperature by Station" in the Tasks pull-down menu.



Number Of Stations: 36

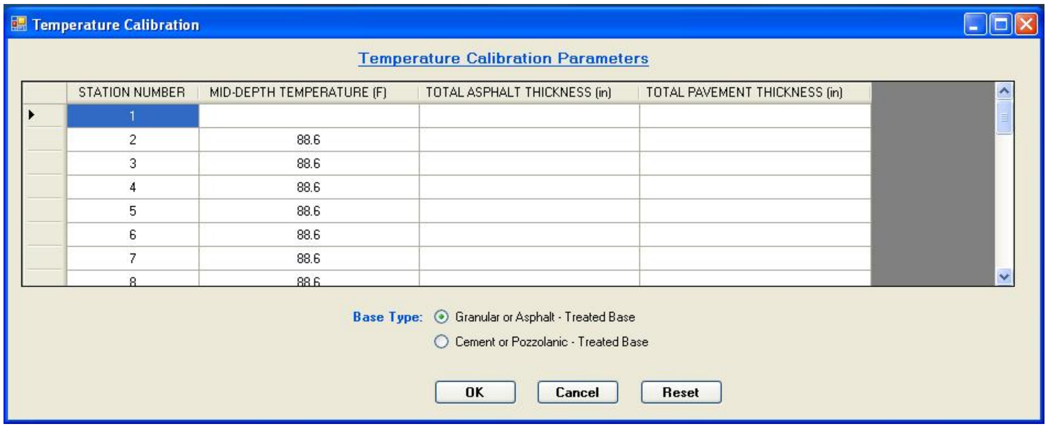
Date (mm/dd/yyyy): 04/19/2006

A Temperature Calibration dialog box will appear.

- Input "MID-DEPTH TEMPERATURE (ºF)" for asphalt concrete layers at each measurement stations.

  Note: If the mid-depth temperatures have been incorporated in the FWD file, then no need to fill in the column of "MID-DEPTH TEMPERATURE (ºF)," the software will automatically read in the data from the FWD file.
- Input "TOTAL ASPHALT THICKNESS (in.)" and "TOTAL PAVEMENT THICKNESS (in.)" in the dialog box.

  Note: At least two stations data are needed. If some stations do not have measured values, interpolation or extrapolation values will be calculated.
- Select the base type from "Granular or Asphalt-Treated Base" or "Cement or Pozzolanic-Treated Base."
- Once inputs are finished and base type is selected, click "OK."
- If "Reset" is clicked, inputted values and the selection choice will be cleared.

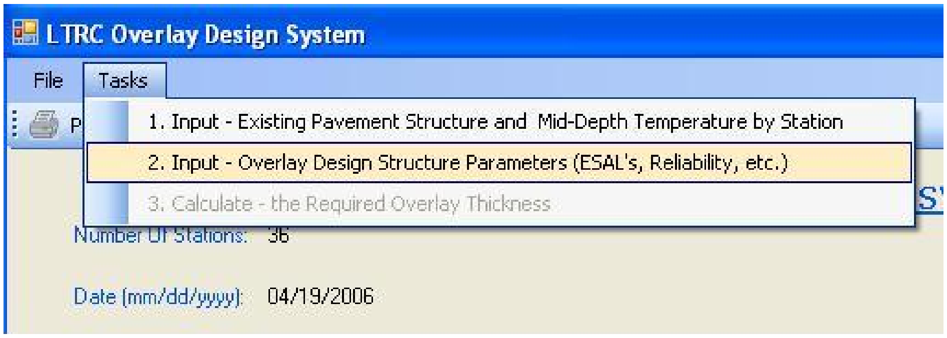


STATION NUMBER	MID-DEPTH TEMPERATURE (F)	TOTAL ASPHALT THICKNESS (in)	TOTAL PAVEMENT THICKNESS (in)
1			
2	88.6		
3	88.6		
4	88.6		
5	88.6		
6	88.6		
7	88.6		
8	88.6		

Base Type: ● Granular or Asphalt - Treated Base
○ Cement or Pozzolanic - Treated Base

3.4. Input Overlay Design Structure Parameters

- Click on “Tasks” in the LTRC-ODP main interface.
- Highlight and click the “2. Input-Overlay Design Structure Parameters (ESAL’s Reliability, etc.)” entry in the Tasks pull-down menu.

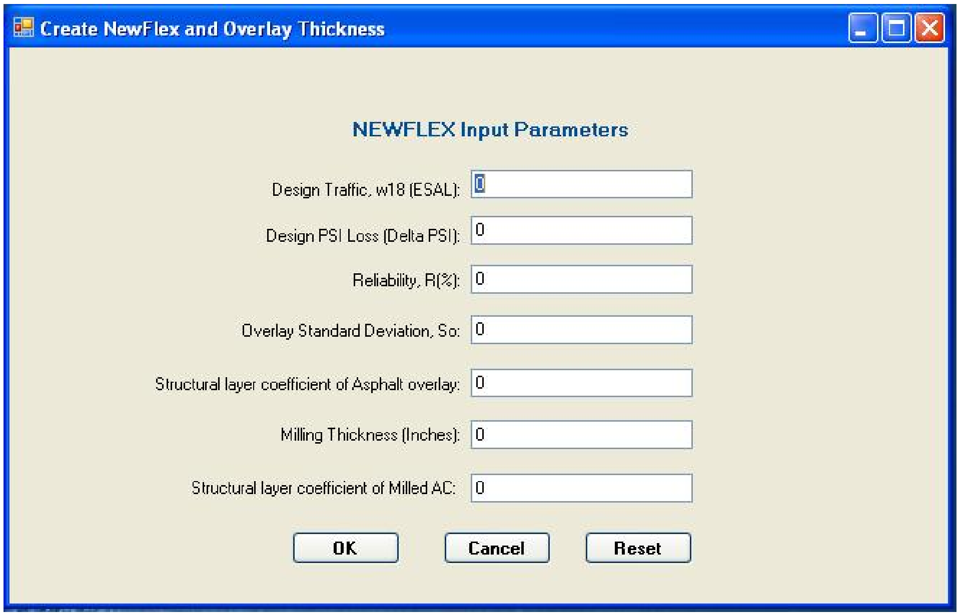


Number Of Stations: 36

Date (mm/dd/yyyy): 04/19/2006

A “Create NewFlex and Overlay Thickness” dialogue box will appear.

- Input the values of Design Traffic, w18 (ESAL); Design PSI Loss (Delta PSI); Reliability, R (%); Overlay Standard Deviation, So; Structural layer coefficient of Asphalt overlay; Milling Thickness (Inches); and Structural layer coefficient of Milled AC.
- Once inputs are finished, click “OK.”
- If the “Reset” button is clicked, inputted values will be deleted.



Design Traffic, w18 (ESAL): 0

Design PSI Loss (Delta PSI): 0

Reliability, R(%): 0

Overlay Standard Deviation, So: 0

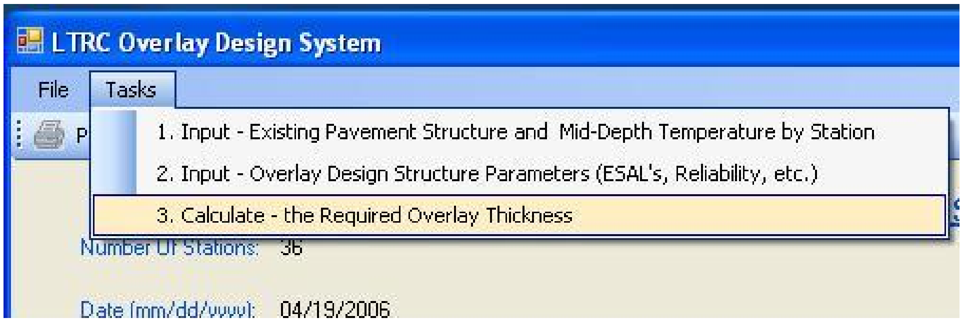
Structural layer coefficient of Asphalt overlay: 0

Milling Thickness (Inches): 0

Structural layer coefficient of Milled AC: 0

3.5. Calculate the Required Overlay Thickness

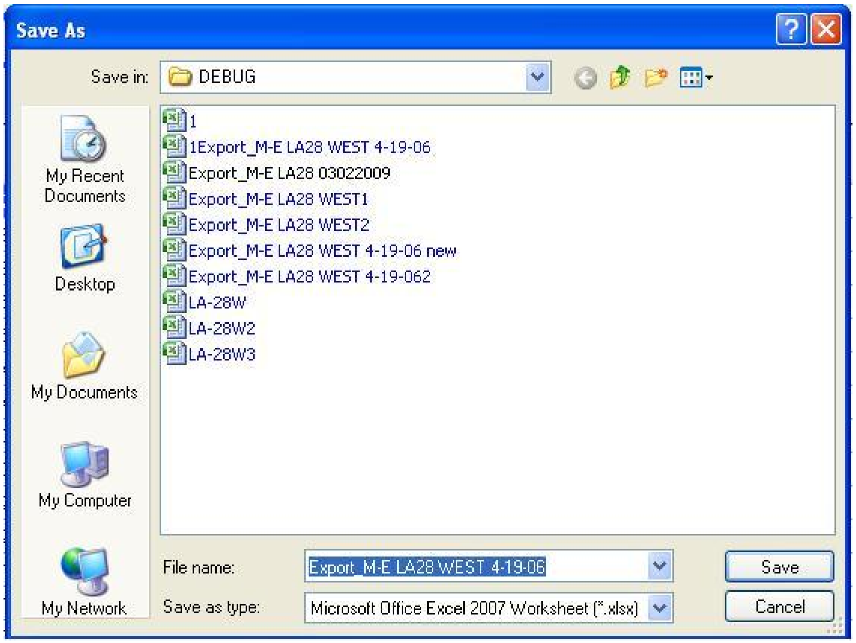
- Click on “Tasks” in the LTRC-ODP main interface.
- Highlight and click “3. Calculate- the Required Overlay Thickness” in the Tasks pull-down menu.



Number Of Stations: 36

Date (mm/dd/yyyy): 04/19/2006

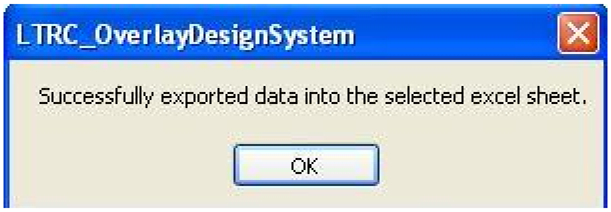
- Select the desired path for the result file, and input the desired name for the result file within the “File Name” dialog box.
- Click “Save” to acknowledge the selection.



File name: Export_M-E LA28 WEST 4-19-06

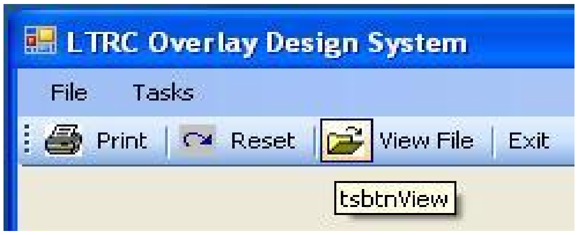
Save as type: Microsoft Office Excel 2007 Worksheet (*.xlsx)

It may take several minutes to save for running software depending on the PC speed. When the calculation is finished, a dialogue box will appear. Click “OK.”



Successfully exported data into the selected excel sheet.

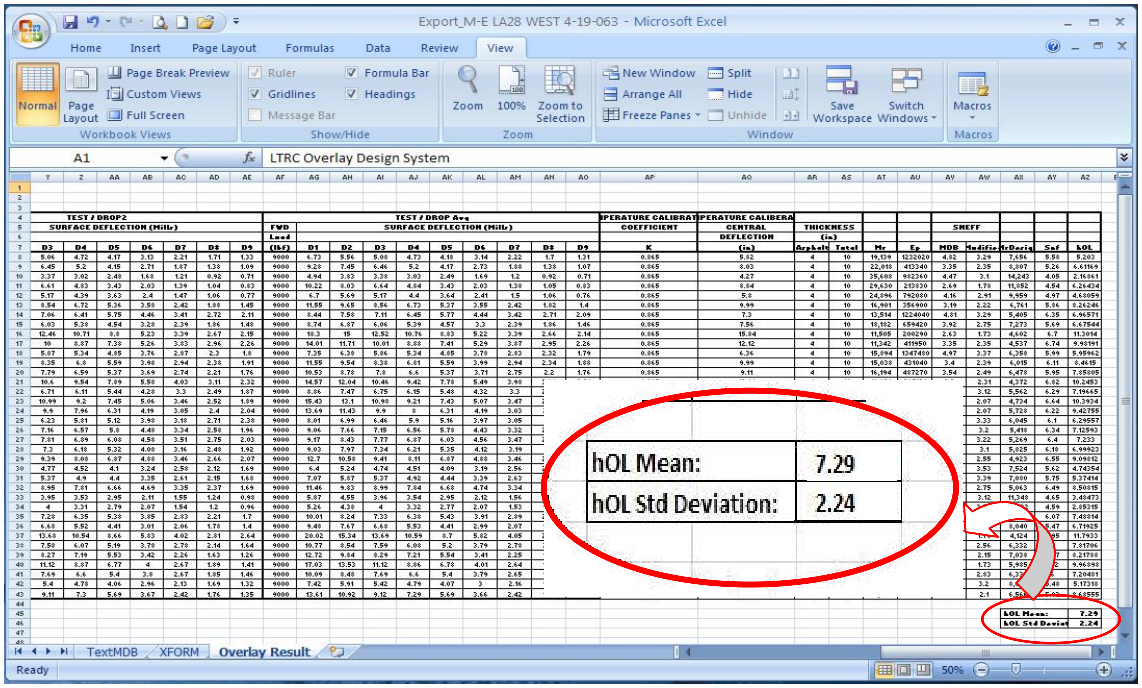
3.6. View Overlay Design Results



- Click the “View File” icon in the LTRC-ODP main menu to open the overlay design result file.

Note: Microsoft Office Excel 2007 Version is needed to view the overlay design results.

The overlay design results are in the Excel file “Overlay Result” worksheet. Detailed calculation information can be found as well. The average and standard deviation of overlay design thickness can be found at the bottom right corner of the worksheet.



LTRC Overlay Design System

hOL Mean:	7.29
hOL Std Deviation:	2.24

- Click the “Print” icon in the LTRC-ODP main menu to print out the results.