Technical Paper

ISSN 1996-6814 Int. J. Pavement Res. Technol. 6(4):304-312
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Longitudinal Local Calibration of MEPDG Permanent Deformation Models for Reconstructed Flexible Pavements Using PMS Data

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Abstract: After almost two decades of intense research and development for mechanistic-empirical design, the AASHTO-supported Mechanistic-Empirical Pavement Design Guide (MEPDG) was finally endorsed as an interim guide for trial uses. However, local calibration of the distress models in the design guide is considered to be an essential exercise for any transportation agency before it formally adopts the MEPDG for practical design use. This paper presents the results from Ontario's local calibration of the permanent deformation models in the MEPDG. The study focused on reconstructed and new flexible pavements using field evaluation data in the pavement management system (PMS) maintained by Ontario's Ministry of Transportation (MTO). A unique feature of the study was the longitudinal calibration; that is, the local calibration parameters in the three permanent deformation models were adjusted to predict the field observed rut depths over the whole life span of a pavement section. To avoid multiple local optima of residual sum of squares (RSS) in the local calibration process, constant proportions of ruts in different structural layers were assumed to obtain the layer rut depths. A macro-based automatic procedure was developed for the local calibration. A comparison of the longitudinal calibration and pooled local calibration demonstrated the importance of the longitudinal calibration in the quantification of uncertainties involved in local calibration and the significance to pavement reliability.

DOI:10.6135/ijprt.org.tw/2013.6(4).304

***Key words**: Flexible pavement; Local calibration; Mechanistic-Empirical pavement design guide (MEPDG); Permanent deformation models.*

Introduction

The Mechanistic-Empirical Pavement Design Guide (MEPDG) developed under multiple NCHRP projects including 1-37A, 1-40 and 9-30A over more than 15 years, has established a very comprehensive and yet flexible working platform that was presented in the official AASHTOWare DARWin-ME^{TM}. The current MEPDG includes both rigid and flexible pavements and covers many pavement structural types that are commonly used in North America. It predicts a great variety of surface distresses, permanent deformation, and overall pavement performance in terms of international roughness index (IRI). By the name, the MEPDG integrates the mechanistic analysis and empirical calibration to consider the complex synergies of traffic loading, material aging, and climatic effects on pavement distresses.

Recently endorsed for trial uses by the American Association of State Highway and Transportation Officials (AASHTO), the MEPDG, however, still needs a lot of research efforts before it can be widely accepted as a practical and reliable design protocol. One of the research needs is local calibration of the distress models used in the design guide. The distress models, also known as the transfer functions, predict the pavement distresses based on the mechanistically computed stress, strain and deformation in structural layers. The local calibration is an important exercise before a transportation agency adopts the MEPDG for actual pavement design. This is because the distress models are empirical by nature and although they have been diligently calibrated and recalibrated to the long-term pavement performance (LTPP) database and other accelerated pavement testing data, the local policies, practices and conditions often differ from the inference space determined by the global calibration database in terms of climate, traffic patterns, material selection, construction methods and maintenance practices. These differences may have significant impact on the predictive accuracy of the distress models in the MEPDG. The local calibration is expected to eliminate the potential biases and reduce the variation of performance prediction [1].

As one of the leading transportation agencies in Canada, the Ontario's Ministry of Transportation (MTO) is considering moving to the MEPDG protocol for future projects. Since 2009 a research project was initialized to develop a local calibration database based on pavement performance data maintained in the MTO's second-generation pavement management system (MTO PMS-2). On the basis of the database the default MEPDG models were evaluated and a need for further local calibration was established [2].

This paper presents the results from a recent local calibration study of the permanent deformation models based on the rutting data stored in MTO PMS-2. The study is focused on reconstructed and new flexible pavements.

Rutting is a fairly complicated phenomenon that results from unrecoverable deformation in all layers of a pavement structural system under repetitive load applications and instability of asphalt material under high temperature [3]. To predict the rut depth, the MEPDG relates rut depth directly and solely to the vertical permanent deformation of different structural layers based on three different transfer models linking the resilient strain to plastic strains

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Note: Submitted February 1, 2013; Revised June 23, 2013; Accepted June 24, 2013.

for the following three types of pavement materials: hot mixed asphalt (HMA) or simply asphalt concrete (AC) layer, unbound granular materials (or simply the base and/or subbase layers), and the fine-grained materials (or the subgrade soil). For the HMA layers, the transfer model is expressed as

$$\varepsilon_{ACp,i} = \beta_{AC1} k_z \varepsilon_{ACr,i} 10^{-3.35412} N^{0.4791\beta_{AC2}} T^{1.5606\beta_{AC3}} \quad (1)$$

where $\varepsilon_{ACp,i}$ and $\varepsilon_{ACr,i}$ are the plastic and resilient strains, respectively, at the mid-depth of the ith analysis layer; k_z is a depth confinement factor that is a function of the layer depth from the surface and the total HMA thickness; N is the number of axle-load repetitions; T is the pavement temperature in Fahrenheit degree; and $\beta_{AC1}, \beta_{AC2}, \beta_{AC3}$ are the local calibration parameters which equal 1.0 in the default global model.

The transfer functions for the unbound granular materials and fine-grained soil have the same functional structure with a different scaling factor. The notations of the transfer function used in the MEPDG documents are confusing for people who are not familiar with the history of model development. With some simplifications, the transfer function can be expressed as the following:

$$\varepsilon_{p,i} = k_s \beta \varepsilon_{r,i} \phi(N, \alpha) \quad (2)$$

where $\varepsilon_{p,i}$ and $\varepsilon_{br,i}$ are the plastic and resilient strains at the mid-depth of the ith analysis layer of unbound granular or fine-grained materials; k_s is the global calibration coefficient, which equals 1.673 for granular materials and 1.35 for fine-grained materials; β is the local calibration parameter which equals 1.0 by default in the global model (in this paper, we use β_{GB} and β_{SG} for the granular and fine-grained materials, respectively); α is a transformed parameter describing the moisture content (W_c) in soil ($\log\alpha = -0.61119 - 0.017638 W_c$). Finally, $\phi(N, \alpha)$ describes the effects of traffic loading and moisture content, details of which can be found in [3].

These three transfer functions include in total five local calibration parameters: three in the HMA model ($\beta_{AC1}, \beta_{AC2}, \beta_{AC3}$), one in the unbound granular materials (β_{GB}), and one in the fine-grained materials (β_{SG}).

A unique feature of the study was the longitudinal calibration; that is, the local calibration parameters were adjusted to predict the field observed rut depths over the whole life span of a pavement section. This is in contrast with the global calibration and other local calibration studies of which the objective was simply to minimize the overall residual sum of squares (RSS) of all tested pavement sections. The main purpose of the longitudinal calibration is to explore an innovative approach to quantifying the uncertainties involved in the distress models. All MEPDG analyses in this study were run in DARWin-ME™ Version 1.0 Build 1.0.18.

In the following, a literature review is presented at first, summarizing the methodologies used for global and local calibrations of the rutting models. Before the new local calibration methodology is introduced, one needs to appreciate the complexity in local calibration arising from the multiple local optima. After this, we propose several investigations to address the local optimal issue. The longitudinal calibration methodology used in the study is then proposed, followed by results and discussions. The paper is concluded with major findings and recommendations.

Literature Review on Global and Local Calibrations

The major achievement of NCHRP project 1-37A is the development of the *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures* [4], in which global calibration of the distress models were performed using mainly LTPP database. To some extent, the global calibration followed a very similar procedure of local calibration. First of all, a large number of experimental data were aggregated to select the best transfer model structures and establish the basic parameters of the transfer models selected. This is considered as the basic models in global calibration. After that, a set of global calibration coefficients are applied to the basic parameters. These global calibration coefficients are then determined by fitting the model to a global calibration dataset, which in general is the LTPP database. NCHRP 1-37A used 88 sections, 387 data points for the global calibration of the permanent deformation models. Because the permanent deformation models involved five global calibration coefficients, NCHRP 1-37A took a four-step approach: (1) The two exponent parameters in the AC model were determined through an optimization process. (2) The two scaling factors for the granular base/subbase and subgrade soil were found from the AASHTO study and the LTPP section optimization. (3) A limited number of trench observations from MnRoad sections were used to determine the depth confinement factor k_z for the asphalt layer. (4) The scaling (or bias) parameter of AC layer was obtained through minimization of the total error. Because of the LTPP database included only surface rutting depth and no trench rut depth was available, the global calibration assumed that proportion of the observed rut depth in different layers follows the same proportion in the predicted rut depth.

An independent review of the MEPDG was done under NCHRP project 1-40A [5]. The review raised a number of issues that need to be resolved before effective implementation of design guide. One of them is the comparison of other transfer models and possibility of including them as alternative models for end users to select. This led to another NCHRP project, i.e., 9-30A [6], the final report of which was released in early 2012. Based on an enhanced rutting database, three additional rutting models were introduced for adoption in future DARWin-ME™ software.

In 2008, a Manual of Practice for the MEPDG was published for trial use [7]. To facilitate the methodology for local calibration, AASHTO published in 2010 the Guide for the Local Calibration of the Mechanical-Empirical Pavement Design Guide [1]. Although this Guide provides the general principles for local calibration, it does not specify in detail the optimization process. Many challenging issues in local calibration were left for the local calibrator to address.

Many DOTs and transportation agencies have initiated local calibration studies based on either LTPP or PMS database. Generally these studies were focused on sensitivity, evaluation and validation and local calibration. Although the main objective of all calibration is to reduce the bias and standard error, the calibration approaches differ from one other in many ways. A few comprehensive local calibration studies for the permanent deformation models are summarized below.

Banerjee et al. conducted local calibration for Texas's conditions [8]. Texas was divided into 5 different regions, and average calibration coefficients these regions were used as the calibration coefficient of Texas. In AC rutting model only β_{AC1} and β_{AC2} were varied while, β_{AC3} was kept the default value of 1 under the assumption that the temperature dependency of a specific material should be determined in the laboratory for a given mix. Subgrade permanent deformation calibration factors values were derived from expert knowledge. The results of five regional level-2 calibrations were pooled by average calibration coefficients.

Li et al. [9] performed section-by-section local calibration for pavement sections under Washington State DOT. Regional studies showed no rutting in subgrade, hence subgrade rutting calibration factor (β_{SB}) was set at zero. Local calibration was performed by categorizing pavement section in 18 possible subgroups based on 3 traffic ranges, 2 subgrade soil types with different resilient modulus and 3 different climates (3 × 2 × 3 = 18). However, many of these subgroups had no section available, leaving eight actual subgroups.

Hoegh et al. [10] performed local calibration of the MEPDG rutting models for 12 pavement sections under the Minnesota Department of Transportation research facility (MnROAD). They observed an abrupt increment in the predicted rutting for first month, so instead of calibrating the calibration coefficients they followed an unconventional approach by not considering the rut depth associated to the first-month of pavement life cycle in the base and subgrade layer. It was observed that this approach of modification in the summation formula of rut depth resulted in better prediction of rutting for pavement sections under MnDOT.

The study of Jadoun [11] was unique in a sense that before local calibration, material properties and permanent deformation performance characterization were developed for all 12 asphalt mix used in North Carolina.

In Alberta, Canada, He et al. (2011) conducted a similar Level 3 calibration for the MEPDG rutting models based on DARWin-ME^{TM} by using the long-term field data (about 20 years) from Alberta's PMS [12]. Instead of checking the rut depth at a project/section level, they adopted a network level approach. Specifically, the inventory sections were divided into three categories, fourteen groups depending upon various pavement characterization factors including rehabilitation, pavement materials and structures, and traffic volume. This grouping strategy was based on the hypothesis that the rutting pattern in these three categories should be different. DARWin-ME^{TM} analyses were then performed using group-averaged parameters in terms of pavement structures, performance, traffic, and climate characteristics. From the study they concluded that DARWin-ME^{TM} over-predicts rut depth of new sections with non-stabilized granular base whereas sections after rehabilitation involving milling are often moderately under-predicted. But DARWin-ME^{TM} provides fairly close prediction for total rutting of sections rehabilitated by straight overlays with no milling.

Multiple Local Optima

The ultimate goal of local calibration is two-fold: to eliminate the possible bias and to minimize the residual sum of squares (RSS). The two objectives are usually compatible, i.e., reducing the absolute bias often minimizes the RSS and vice versa. Therefore, it is common in local calibration to focus on only the RSS.

For a specific pavement sections with observed total rut depth d_j and calculated total permanent deformation D_j at different inspection time t_j, the RSS is defined as

$$RSS = \sum_{j=1}^{n} \left(D_j - d_j\right)^2 \tag{3}$$

Note that D_j depends on the five local calibration parameters $\beta_{AC1}, \beta_{AC2}, \beta_{AC3}, \beta_{GB}, \beta_{SG}$. Therefore, it has been expected that an optimal value of the local parameters could be obtained by simple minimization of the RSS. For this, many people used Excel Solver or MATLAB optimization toolbox to find the numerical optima. It has also been thought that a unique solution could be expected. However, our study showed that there were actually multiple local optima in the RSS minimization problem.

To understand this, extensive computer iterations of a typical pavement section (Section 1200) from the local calibration database developed in [2] were run in DARWin-ME^{TM} to plot surfaces between the local calibration parameters and the RSS. In these iterations the two exponent parameters β_{AC2} and β_{AC3} were kept to be the default value of 1 while all possible permutations of β_{AC1}, β_{GB} and β_{SB} from 0.1 to 1.0 at a constant interval of 0.1 were used for analysis. As shown in Fig. 1, at least two combinations of β_{AC1} and β_{SG} provides similar minimized RSS values. Due to space limit, the other contour plots with different combinations of the three parameters at different levels are not shown here. In fact, when the three scaling parameters are allowed to vary, there are more than 17 local optima that resulted in a RSS of less than 4. Fig. 2 shows five of these local combinations and the correspondingly predicted total rut depth against the observed values. Although the local calibration parameters are very different, the predicted rut depth curves are very close. The presence of the multiple local optima makes the local calibration of rutting models very complicated.

Layers Contribution to Rutting

Because of the multiple local optima in the RSS minimization, some researchers used evolutionary optimization algorithms (e.g., the genetic algorithm in [11]) trying to get a so-called global optimal solution. This approach blurs the nature of the problem and thus not used in this study. The root cause of the multiple optima is actually the indeterminacy of the transfer functions. As discussed above, the three transfer functions collectively determine the total surface rut depth. However, the local calibration is doing the opposite, i.e., use the total surface rut depth to determine the three functions. In order to uniquely determine the five local calibration parameters in the three functions, one needs to reduce the inherent indeterminacy of the permanent deformation models. The only reliable approach to this reduction is through the layer contribution to the total surface rut depth, i.e., how much percentage of the total rutting comes from the AC surface layer, base layer, subbase layer, and the subgrade soil? Once this information is available, unique determination of the five local calibration parameters can be expected. The details of the local calibration methodology are explained in the next section.

Before that, the actual percentages of layer contribution to rutting

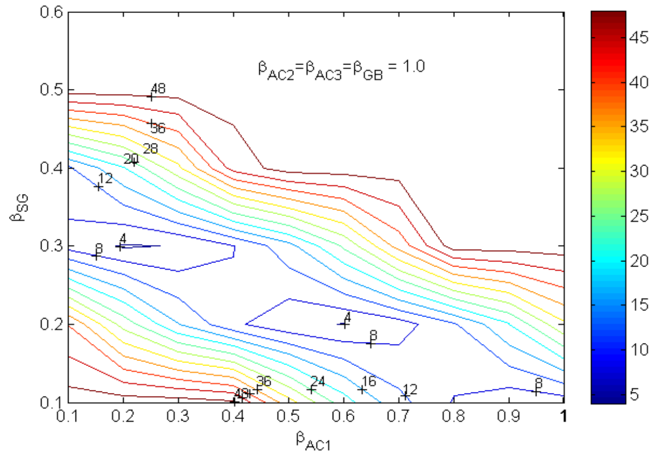

Fig. 1. RSS Contours Against $\boldsymbol{\beta_{AC1}}$ and $\boldsymbol{\beta_{SG}}$ Dhowing Multiple Local Minima.

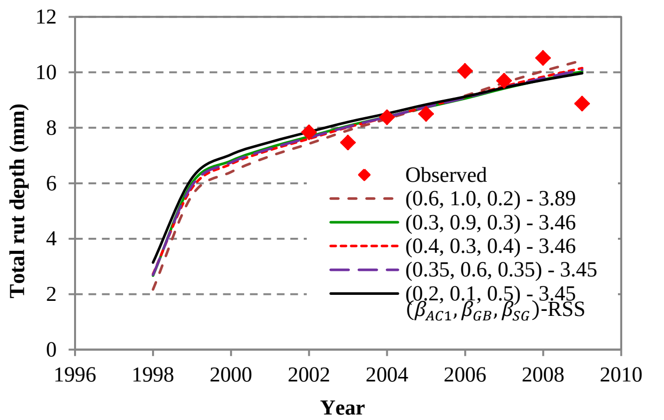

Fig. 2. Predicted Total Rut Depth Curves with Different Combinations of Calibration Parameters.

Table 1. Layers Contribution to Surface Displacements from Linear Elastic Multi-layer Programs.

Software Package	Asphalt Concrete [%]	Granular [%]	Subgrade [%]
WESLEA	2.63	11.54	79.67
KenPave	2.97	19.35	77.68
mePADS	5.88	24.18	69.93

need to be sorted out. A direct way of determining the layer contribution would be the field trench analysis that the MEPDG research team advocated long time ago. This method is not very practical for local calibration for two reasons. The first one is that the trench analysis is very expensive and time consuming. The second one is that even a dedicated transportation agency would like to conduct some trench analysis, a series of follow-up trench investigations are important to ensure the reliability of the data observed. For these reasons, this study took an indirect approach. Basically, previous empirical studies were reviewed first to understand the statistics of the layer contributions. It was then followed by computational analyses using various software packages with different deformation theories, hoping additional insights could be gained that would help us to determine a reasonable combination of the layer contribution percentages. Results from these studies are reported below.

Empirical Studies

Several trench studies have been done as a part of other projects to estimate layer contribution to rutting in U.S.A. The AASHO report (1962) [13] conveyed that rut could attributes to changes in thickness of 32% in surface, 14% in base, 45% in subbase and 9% in subgrade of the total rutting; these proportions were also cited in [14].

Zhou and Scullion [15] extracted rutting using multi-depth deflectometers to determine the observed layers contributions to total rutting for Texas pavement sections. They found that the percentage contributions to rutting in AL-TxMLS varied along the service life of pavement [15].

An another study reported in [16] is ALF-FHWA field observations, in which layer contribution to rutting was classified in two categories based on thickness of surface layer (thick and thin). In same study based on 109 in-service pavement sections in the LTPP Special Pavement Study-1 (SPS-1), the contribution to the total surface rutting from the various structural layers, on average, was summarized as follows: 57% from the AC layer, 27% from the base layer, and 16% from the subgrade. This finding was found to match very well the observations made in [15] for ALF-TxMLS (Accelerated Loading Facility-Texas Mobile Load Simulator) data.

Layers Contribution to Rutting from Software Packages

Another approach is to use the percentage contribution to elastic displacement as a surrogate to emulate the percentage contribution to the permanent deformation. Three linear elastic multi-layer programs named WESLEA, KenPave and mePADS were used to estimate the surface displacement in a typical flexible pavement structure design in Ontario (22 cm AC layer, 15 cm granular base, 45 cm granular subbase, and silty sand subgrade with M_r = 25 MPa). Similar results as shown in Table 1 for displacement in the pavement were obtained from all three software packages. The software generated results predict much higher rutting in subgrade and negligible rutting in AC layer. Therefore, this approach turned out not to be trustable.

Findings from DARWin-ME^{TM} Global Models

The third approach to indirectly determining the layer contribution to rutting is to use the same layer contributions in DARWin-ME^{TM} of the default global models. This approach was actually used in NCHRP 1-37A for global calibration.

The default models were used to analyze 10 reconstructed pavement sections in the local calibration database. The average percentage contribution of rutting from each layer along service life is shown in Fig. 3. It is observed that the percentage rutting associated to subgrade and granular base layer decreases with the service life while that of asphalt concrete layer increases. The life-long average observed contribution of rutting was 20% in AC layer, 12% in granular base/subbase layer, and 68 % rutting in subgrade layer.

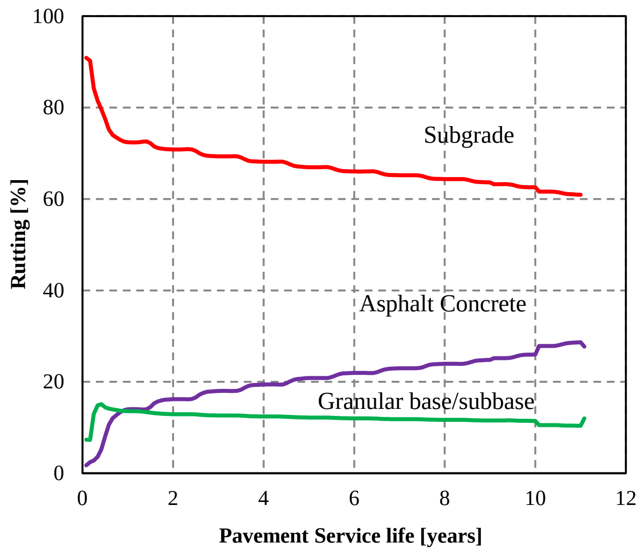

Fig. 3. Average Percentage Layer Contribution of Rutting.

To summarize, research on layer contribution to rutting was done from several aspects. Contradicting results were found from global default models, elastic multilayer computer packages and studies. These values were compared with rutting contributions measured during former studies in USA. In Ontario, this topic has not been seen in literature. In the following study, the layer contribution of rutting measured by AASHO in 1962 (i.e., 32% for AC, 59% for granular layers and 9% for fine-grained soil) was selected as the main scenario for local calibration of new and reconstructed pavement sections.

Local Calibration Methodology

Based on previous discussion, the AASHO layer rutting contribution percentages are used to calculate the observed rutting in all layers as a percentage of the observed total surface rutting. Meanwhile, the layer rut depths are predicted by using DARWIn-ME^{TM}. The RSS of each individual structural layer is calculated by comparing the observed layer rutting and the DARWin-ME^{TM} predicted layer rutting. Minimization of the layer RSS leads to the optimal value of the corresponding local calibration parameters.

Local calibration of granular and subgrade are relatively straightforward due to a single multiplier calibration factor β_{GB} for base and β_{SG} for subgrade. Denote by d_i the measured layer rut at the ith observation year, and by D_i the calculated layer rut based on the default global model at the same time of observation. Then for a different local calibration factor β, the calculated layer rut will e βD_i. The simple first-order optimality rule for the minimization of $RSS = \sum(d_i - \beta D_i)^2$ yields

$$\beta = \frac{\sum d_i}{\sum D_i} \tag{4}$$

in which the summation is over the whole range of observation points.

The presence of the three calibration factors ($\beta_{AC1}, \beta_{AC2}, \beta_{AC3}$) in HMA rutting model involves a large amount of computational effort, as it requires iteration and the convergence can be very slow. The two stage layer-by-layer, section-by-section local calibration process was developed and semi-automated using DARWin-ME^{TM} coupled with Excel Macros for the calibration of AC model. This methodology involves iterative optimization of a response surface model, which is used as a surrogate for the DARWin-ME^{TM} prediction during the optimization process. Each section was individually calibrated for the available rut points throughout the service life of the pavement which is called the section-by-section longitudinal calibration.

The above-mentioned local calibration process was automated by making use of DARWin-ME^{TM} project input file saved with .dgpx extension. Coded in an *Extensible Markup Language* (XML) the input file is both human-readable and machine-readable. This allows one to create and apply Macros to edit the project files in an automatic manner. Other macros were developed in Microsoft Excel to automate the process of generating desired files and reports. This saves a lot of time in local calibration when software is needed to run hundreds of variations of same project with different set of calibration coefficients.

Pavement Sections and Database

Ten pavement sections from the local calibration database developed in [2] were selected for this study, with characteristics shown in Table 2. Because the actual rutting values were not measured in Ontario until 2002, while majority of PMS-2 flexible pavement sections starts their life cycles (either new, reconstructed or rehabilitated) before 2002, all of the ten sections were reconstructed pavement section and none of them was a new section.

The local calibration database includes level-2 and level-3 input parameters for material and traffic of selected pavement sections. Input parameters such as project sites, pavement structures, types of layer materials, traffic volume, truck percentage and traffic growth factor were site specific and they were taken from the local calibration database developed recently based on the MTO's PMS-2 database and contract documents; for more details refer to [2]. Other Level 2 or Level 3 inputs such as asphalt concrete (AC) and granular material characterizations, and traffic loading data (e.g. axle load distribution, typical axle per truck, tire configuration) were taken from the default values recently developed by the MTO staff [17].

Results & Discussions

The permanent deformation models are calibrated to the ten pavement sections by using the local calibration methodology described above. The three local calibration parameters for each section based on the longitudinal calibration are listed together with the corresponding RSS, bias and percentage layer contributions in Table 3. Layer percentage contributions in each layer were similar to the selected percentage contributions for observed layer (e.g. ≈32 for AC layer, ≈59 for granular layer and ≈9 for subgrade layer).

Large variation is observed in the final local calibration parameters. The AC scaling parameter β_{AC1} varies from 0.162 to 0.470. Because of the large difference in the percentage contribution

Table 2. Characteristics of Pavement Sections.

Section ID	Zone	Highway	Design Life [years]	Total AADTT	No. of Total Layers	Total AC Thickness [mm]	Top AC Layer	Total Granular Thickness [mm]	Subgrade Modulus [MPa]
9	SO	1	11	17,025,000	6	260	DFC	400	35
43	SO	1	11	22,700,000	6	260	DFC	400	35
191	SO	7	18	7,208,550	6	330	HL-1	450	40
376	NO	11	11	2,634,600	5	130	HL-1	870	27.6
1049	SO	401	14	52,901,200	4	250	DFC	640	38
1053	SO	401	9	18,650,400	5	240	DFC	650	15
1188	SO	402	10	7,809,230	6	220	HL-1	600	31
1189	SO	402	11	8,522,460	6	220	HL-1	600	25
1200	SO	402	11	8,190,480	6	220	HL-1	600	25
1311	SO	417	10	3,921,290	6	140	HL-1	600	17.2

Table 3. Section-by-section Longitudinal Local Calibration Results.

Section ID	Rutting Model					Layers RSS			Total Bias	Total RSS
	AC			Granular	Subgrade					
	β_{AC1}	β_{AC2}	β_{AC3}	β_{GB}	β_{SB}	AC	Granular	Subgrade		
9	0.144	1.738	0.229	3.06	0.033	0.063	0.2378	0.0074	0.120	0.660
43	0.162	1.091	0.920	3.17	0.033	0.098	0.2281	0.0051	-0.075	0.564
191	0.290	0.975	1.105	1.57	0.039	0.022	0.2128	0.0047	-0.002	0.436
376	0.310	1.20	0.835	0.41	0.025	0.309	1.0798	0.0243	0.038	2.693
1049	0.196	0.991	0.985	0.96	0.037	0.257	0.7121	0.0163	-0.018	1.972
1053	0.256	1.262	0.719	0.63	0.016	0.097	0.3104	0.0070	0.055	0.806
1188	0.370	1.040	0.970	1.11	0.040	1.064	0.4038	0.0082	-0.737	2.935
1189	0.470	1.130	0.870	1.27	0.041	0.383	0.2239	0.0055	-0.303	1.064
1200	0.368	1.480	0.580	1.61	0.050	0.454	1.3401	0.0363	-0.319	3.444
1311	0.336	1.182	0.892	0.66	0.022	1.105	2.8296	0.063	-0.158	8.235

Table 4. Section-by-section RSS [mm^2] Based on the Pooled Local Calibration Results.

Section ID	AC	Granular	Subgrade	Total Rutting
9	4.06	21.88	0.01	8.67
43	7.61	23.45	0.01	5.49
191	1.68	7.8	0.04	18.38
376	1.83	47.89	0.07	36.51
1049	10.95	2.14	0.06	5.45
1053	2.14	2.93	0.54	14.78
1188	2.63	6.86	0.13	20.69
1189	4.72	14.97	0.19	41.59
1200	19.84	58.13	0.94	169.59
1311	6.74	6.25	0.3	8.08
Subtotal	62.2	192.3	2.29	329.24

from the subgrade soil based on the AASHO study and that from the MEPDG default model (9% vs. 68% as discussed previously), the subgrade soil parameter β_{SG} is extremely small, ranging from 0.016 to 0.050. Meanwhile, since the AASHO study showed a major contribution of the total surface rutting was from the base and subbase layers, the granular base/subbase calibration parameter β_{GB} varies across the default value of 1. The lowest value is 0.41 for section 376 while the greatest value 3.17 for section 43. The averages of optimal values for the three parameters of the ten sections are 0.40, 1.45 and 0.03, respectively. The reason for the large variation in the local calibration parameters is not clear and it needs further study in future.

It is observed that except for Sections 1200 and 1311, the local calibration results in very small bias and RSS. For all sections, the percentage layer contributions averaged along the observational life has maintained to be consistent with the pre-defined percentage contributions of the AASHO study.

For comparison purpose, a pooled longitudinal calibration was also performed. The pooled calibration was the common approach that was seen reported in previous local calibration studies. Basically the rutting data from different sections are all pooled together to calculate the total RSS which is then minimized a single set of optimal calibration parameters. In this study, the two exponent parameters β_{AC2} and β_{AC3} were kept constant at 1. The total RSS was minimized at $\beta_{AC1} = 0.3, \beta_{GB} = 0.8$ and $\beta_{SG} = 0.03$, which are different from the averaged value in the section-by-section calibration, particularly for β_{GB}. The section-by-section RSS based on the pooled calibration are also shown in Table 4. In terms of layer RSS and total RSS, the residuals from the pooled calibration are much greater than those from the section-by-section calibration.

Comparing the plots of residual errors of predicted total rut depth (Fig. 4) showed that for section by section calibration residuals errors were equally scattered on both sides of zero line, whereas for pooled calibration for total rut less than 5 mm observed rutting were larger than predicted rutting and vice versa.

Another way of comparing the two calibration approaches are through the prediction versus observation plots (Fig. 4). The

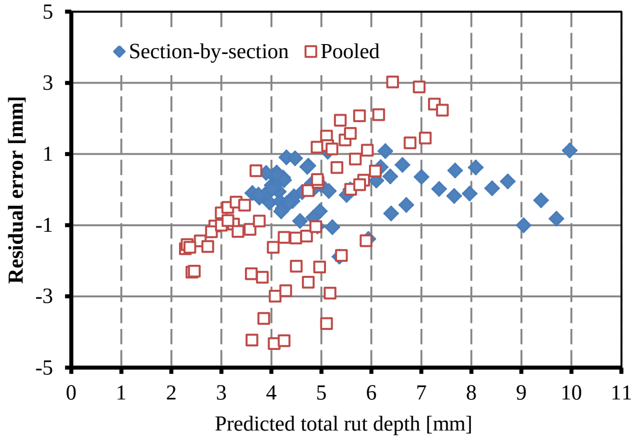

Fig. 4. Residual Errors for Total Predicted Rut Depth After Calibration.

section-by-section calibration gave exceptionally efficient results with a R^2 value of 0.88 which shows extreme correlation between the predicted and observed values. As expected, the pooled calibration shows extremely poor correlation (0.016) with relatively high standard error of 2.217.

The two local calibration results are also compared with the global calibration results in terms of the standard deviation. As shown in Table 5, it is argued that although the pooled calibration revealed very poor correlation between the predicted and observed rutting, the resulting overall standard deviation (2.22 mm) is actually comparable to the result from the global calibration, which was based on a much larger data set. It is also argued that the small standard deviation in section-by-section longitudinal calibration (0.57 mm) may be an underestimate of the uncertainty involved in local calibration, because the errors involved in point-by-point rut depth measurements and post processing of the point data can be much greater than this value. This brings up an issue of over-calibration in local calibration exercise. However, the current local calibration Guide [1] did not provide much guidance in addressing this issue. Further study is obviously needed.

Similarly, for comparison purpose prediction versus observed plots for asphalt concrete, granular and subgrade layer were plotted in Fig. 6. All layers plots gave similar correlation value, however the standard error in each layer was distributed according to the percentage contribution of rutting used to obtain observed rutting in each layer. The highest standard error was in granular layer of 0.336, while standard error in asphalt and subgrade layer was 0.240 and 0.0515.

Longitudinal comparison of predicted layer rutting for Section 376 is shown in Fig.5. While the section-by-section calibration provides accurate prediction, the predicted rutting based on the pooled calibration is far off from the observed rutting as compared to AC or Subgrade rutting predictions. Predictions from global models are not included in this comparison as they extremely over predict the rutting for all layers.

Conclusions

The challenges facing in the local calibration of permanent deformation models and solutions to the challenges are discussed in

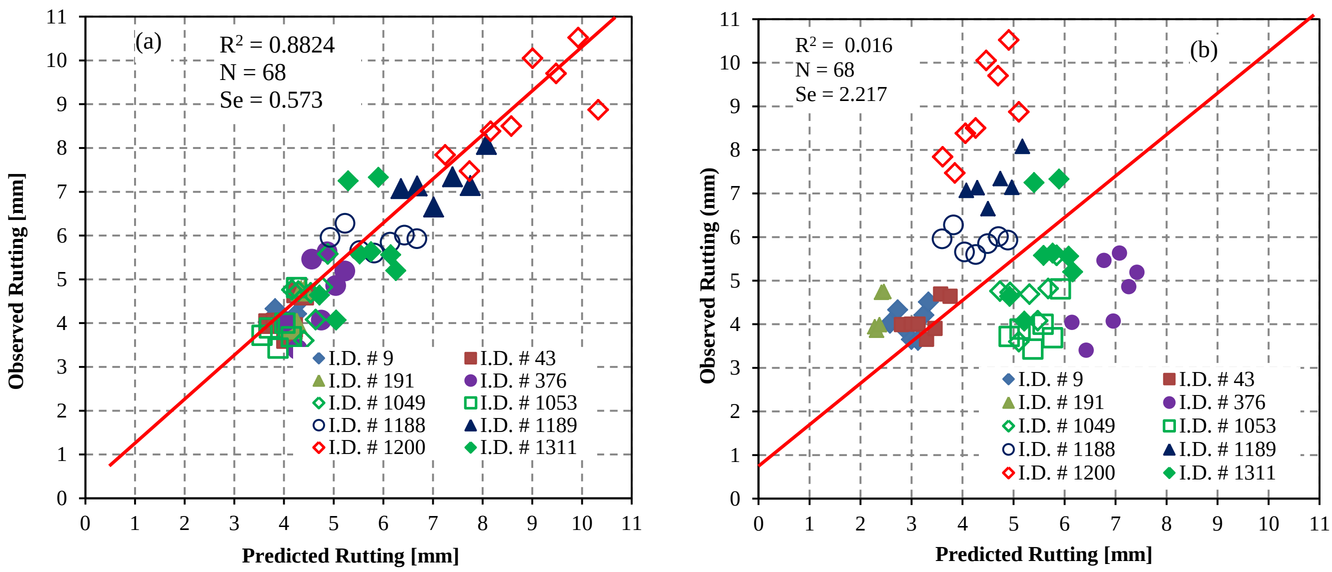

Fig. 5. After-calibration Prediction Versus Observation Plots. (a) Section-by-section Calibration; (b) Pooled Calibration.

Table 5. Comparison of Statistics of Global Calibration and Local Calibration.

Parameters	Global Calibration [4]	Global Calibration [7]	Section-by-section Local Calibration	Pooled Local Calibration
Number of Data Points	387	334	68	68
Standard Deviation [mm]	3.07	2.72	0.57	2.22
R^2	0.399	0.577	0.882	0.016

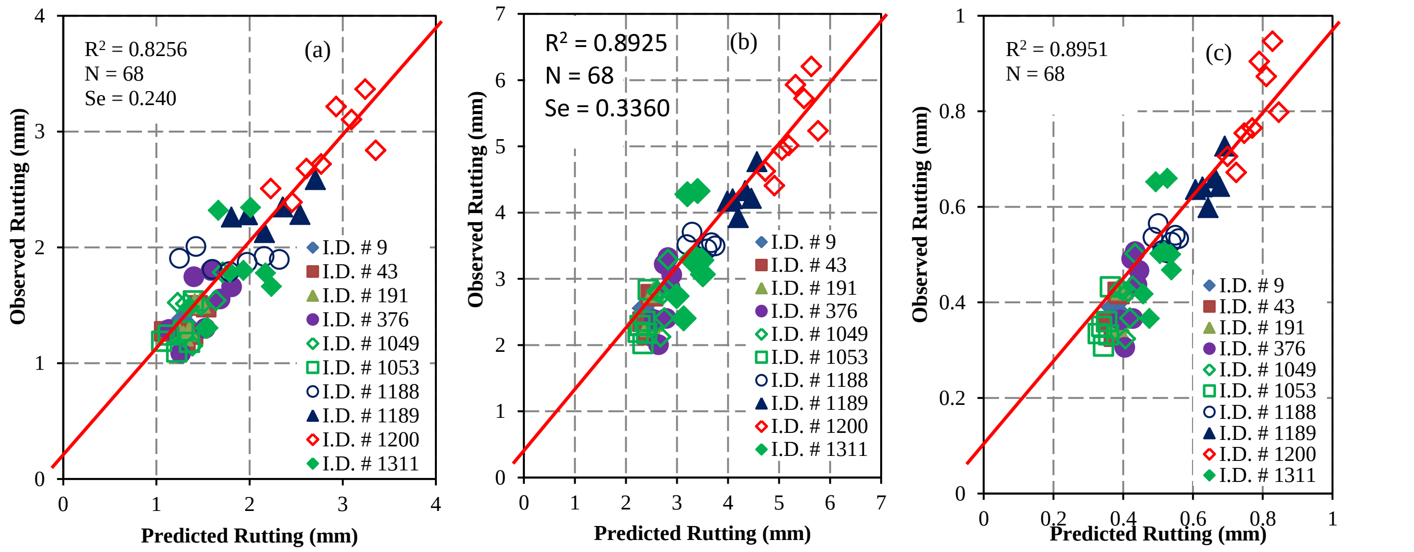

Fig. 6. After- section-by-section Calibration Prediction Versus Observation Plots. (a) Asphalt Concrete Layer; (b) Granular Layer (c) Subgrade Layer.

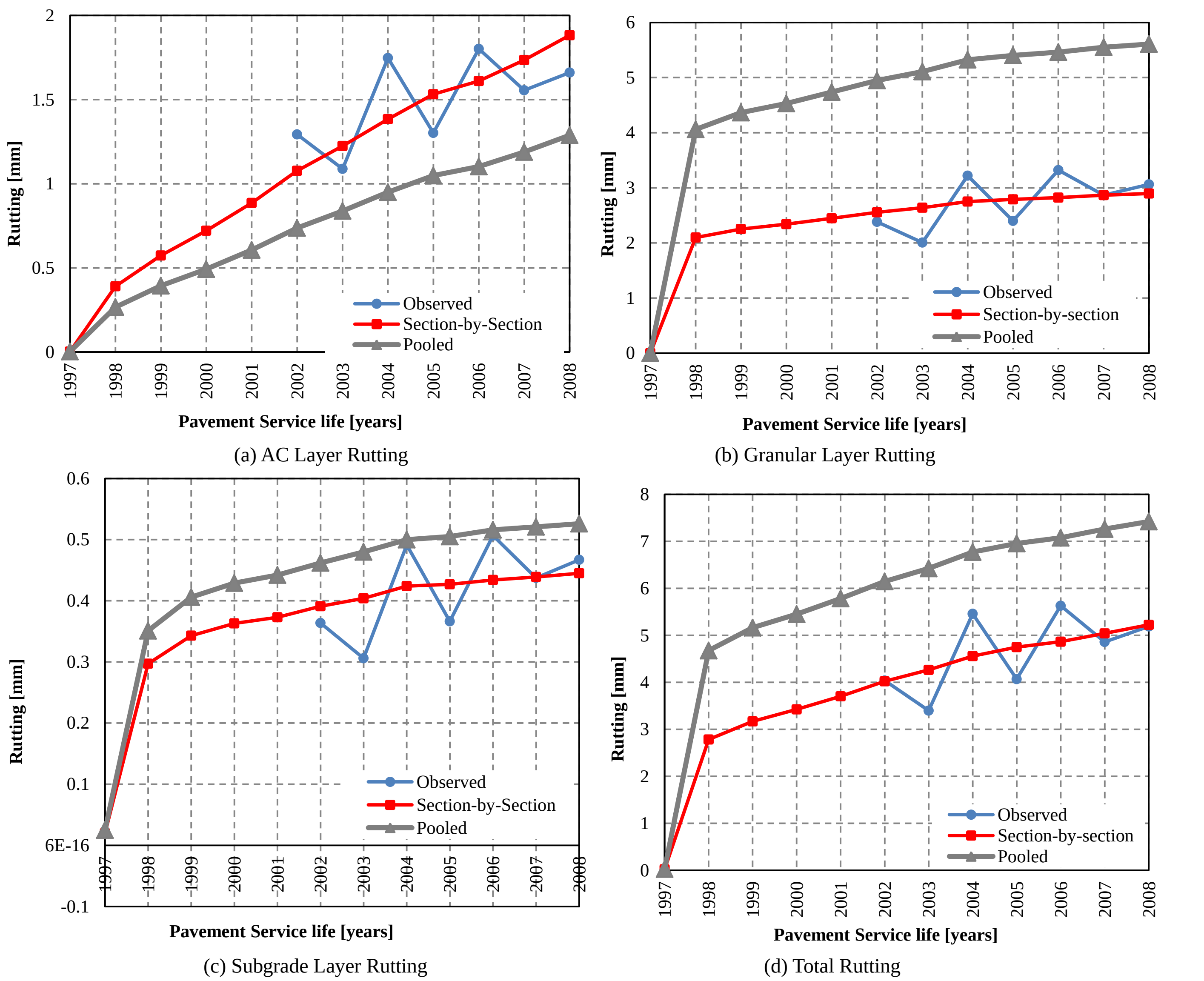

Fig. 7. Longitudinal Comparison of Rutting.

this paper. It has been found that if calibrated for total observed rutting there cannot be a unique optimal solution because of the indeterminacy of the rutting models. To deal with this difficulty, a set of percentage contributions to the total rutting from different structural layers were proposed based on previous empirical studies and computation observations. In the end, a layer-by-layer, section-by-section longitudinal local calibration process was developed and automated using the DARWin-ME^{TM} and Excel Macros.

The local calibration results for ten reconstructed flexible pavement sections selected from the MTO local calibration database have showed that the section-by-section longitudinal calibration is very accurate. However, the calibrated local parameters have very large variation. This large variation may cause additional problem in future implementation of the MEPDG to actual design. On the other hand, the comparison of the section-by-section calibration with the pooled longitudinal calibration has indicated the issue of over-calibration that lead to residuals that are unrealistically smaller than the measurement errors of rut depth. These were the new issues that are open for further study.

Acknowledgement

This research is funded by a grant from the MTO under the Highway Infrastructure Innovation Funding Program. The financial support of this organization is highly appreciated. The authors would like to thank Mr. Warren Lee of Pavement and Foundation Section of the MTO for providing the MTO documents for default parameters for MEPDG applications.

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