



Method for Assessment of Modeling Quality for Asphalt Dielectric Constant to Density Calibration

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Abstract: Traditional measures of asphalt compaction rely primarily on random cores that only measure a small fraction of the pavement. Recently, the use of ground penetrating radar was indicated to be usable as a nondestructive means for the continuous assessment of asphalt compaction. A proposed Hoegh-Dai (HD) model has been successful in predicting air void content within typically achieved field compaction levels but has reduced accuracy at the extremes. This paper proposes an enhanced Minnesota DOT (MnDOT) model to address this issue. A method for assessing modeling quality is proposed to quantify the improvement of the MnDOT model. The procedure is based on the accuracy of fits when run through a Monte Carlo simulation. The developed procedure indicates that the MnDOT model has improved accuracy—with 0.74% air void variation at a dielectric of 4 compared with 3.83% for the HD fit. Additionally, the MnDOT model is more stable for replicate days of the same mix design and falls within the uncertainty of more of the field cores across several projects than the HD model. DOI: [10.1061/JPEODX.0000210](https://doi.org/10.1061/JPEODX.0000210). This work is made available under the terms of the Creative Commons Attribution 4.0 International license, <https://creativecommons.org/licenses/by/4.0/>.

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Introduction

Recent developments in methods for asphalt compaction evaluation suggest that ground penetrating radar (GPR) can be effectively employed to nondestructively test the relative compaction of the placed pavement. This technology has advanced from noncontact horn antennas (Saarenketo and Roimela 1998) or other methods, such as step-frequency, array-based systems (Hoegh et al. 2015; Leng and Al-Qadi 2014; Scott et al. 2006; Shangguan and Al-Qadi 2015), to smaller, dipole-type antennas that can accurately measure the dielectric constant of a placed asphalt mixture (Wilson and Sebesta 2015). These antennas can be placed on a push-cart or a vehicle mount to allow for the continuous assessment of the placed pavement's air void content. The procedure for calculating dielectric constant values using GPR antennas uses the surface reflection method. This method is based on measuring the reflection amplitude of the air/asphalt interface. The amplitude of the reflection from air to the asphalt surface, relative to the incident amplitude (represented by the reflection from a metal plate), is then used

to determine the bulk dielectric constant of the asphalt. The ability to continuously measure the density of in-place pavement using GPR technologies makes it easier to provide onsite feedback of the paving operations and techniques, as well as a full picture of the pavement compaction quality. Furthermore, given that insufficient asphalt density is the most frequent construction-related performance problem (Killingsworth 2004), the full coverage testing approach made possible by GPR technology improves the ability to quickly identify density deficient areas and, thus, determine the service life of the pavement. Worthwhile to note is that, at present, most quality acceptance programs rely on random coring that measures less than 1% of the produced total asphalt mixture; the cores could misrepresent the true compaction of the full pavement.

The compaction level and air void content of a compacted pavement are two interchangeable characteristics: the higher the compaction, the lower air void content. Because of this relationship, the air void content level of pavements is typically reported by the relative compaction or relative density parameter [Eq. (1)], which quantifies the fraction of the pavement that is not air voids (in reference to the theoretical density):

$$RD = 1 - AV = \frac{G_{mb}}{G_{mm}} \quad (1)$$

where RD = relative density of the pavement; AV = air void content of the mixture; G_{mb} = bulk specific gravity of the compacted mixture; and G_{mm} = theoretical maximum specific gravity of the loose mixture. All three components of an asphalt mixture (asphalt binder, aggregate, and air void) contribute to the measured dielectric constant. Hence, several mix characteristic-dependent models have been developed to predict the dielectric constant for a specific combination of components (Al-Qadi et al. 2010). However, these types of models rely on estimating dielectric constants of the aggregate and binder by back-calculation or from the literature (Al-Qadi et al. 2010). As a result, these models are relatively complex to use on a routine basis. Furthermore, the measured mixture dielectric constant relies on the various components used for the specific asphalt mixture; for example, aggregate type and distribution

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in the mixture have a strong effect on the dielectric constant of the mixture (Teshale et al. 2020). Thus, conversions between dielectric constant and air void content must be determined for each specific mix design. Recently, empirical models that are better suited to capture the daily variability of asphalt mixture productions than existing theoretical models (Haddad and Al-Qadi 1998; Böttcher et al. 1974; Sihvola 1999) have been proposed to facilitate the creation of calibration curves. The most commonly used empirical fits are basic linear and exponential (Hoegh et al. 2015; Popik et al. 2010; Saarenketo and Roimela 1998). The empirical models are calibrated to a specific mix design and require recalibration if the mix design changes significantly. Historically, these empirical models have required the collection of field cores from the placed pavement. However, in 2018, GSSI and Minnesota DOT (MnDOT) researchers indicated that asphalt specimens compacted in a superpave gyratory compactor (SGC) can be efficiently used to create a calibration curve that can convert the measured dielectric constant to the pavement's air void content (Hoegh et al. 2019, 2020). The SGC is commonly used by a certified lab technician to fabricate asphalt specimens at a specified number of gyrations (based on the expected traffic level for the road) to monitor the air void content and density of production mixes. The coreless calibration method described by Hoegh et al. (2019) uses these standard SGC specimens along with additional higher air void content specimens to develop a relationship between the dielectric and the air void content. This new approach provides advantages because it can better represent the overall pavement quality without requiring field cores that are expensive to take and limited in coverage.

The empirical fits can be used to reasonably estimate the air void content of pavement in the 5%–10% range but fail to model the extremes of the data. Recently, a new model, the Hoegh-Dai (HD) model has been proposed to better match the data at the extremes and is the current best empirical fit for the experimental data (Hoegh et al. 2018). The HD model also includes physical bounds on the maximum and minimum values possible with the model, preventing the model from predicting negative air void contents or dielectric constants less than 1. Both the exponential and linear models are unbounded. The HD model addresses these issues by allowing for only positive values of air void percentages, and having a dielectric of 1 corresponds to 100% air voids. The HD model has the form

$$AV = \exp(-B(D^{\frac{1}{c}-1} - 1)) \quad (2)$$

where the parameters B , D , and C are fit to minimize the sum of the difference of the squares between the model and the experimental data; and AV and ϵ represent the modeled air void content and the dielectric constant, respectively.

Although the HD model effectively matches experimental cores with air void contents between 4% and 12%, it fails to match the trends apparent at the farther extremes of the collected field core data. Fig. 1 provides field validation cores and the HD model for trunk highway (TH) 371 (TH 371) and trunk highway 15 (TH 15), and clearly indicates that the HD model overestimates the slope of the air void versus dielectric behavior at the extremes of the data. TH 371 was the most convincing data set based on the higher quantity of field validation cores that were taken. In the figure, both fits are made using gyratory specimens and then compared with the field validation cores. The HD model is almost within the uncertainty of the validation cores. However, the apparent trend at the extremes is not matched, suggesting that the HD model is deficient in its ability to model high air void content data.

Objectives

An adjusted logistic model is proposed in this paper to better match field core behavior and allow for improved quality assurance analysis of pavement compaction. This model, hereafter called the MnDOT Model, expands the range of the fit to cover essentially all reasonable air void contents from a placed pavement. This model is currently being used by the Minnesota Department of Transportation to assess the ability of GPR to be used in conjunction with coreless calibration from SGC specimens (Hoegh et al. 2019). Given improvements to the HD model, a calibration curve can be developed in the laboratory using SGC gyratory pucks without taking field cores that damage the pavement. The method for core-free pavement compaction evaluation is further improved using the new proposed MnDOT model (Hoegh et al. 2019).

In addition to providing an improved empirical fit, this paper details a testing procedure to verify fit accuracy and assess the quality of new empirical models. The basis of the proposed method is a simulation of random fluctuations in the measured dielectric constant and air void content of the SGC specimens and field validation

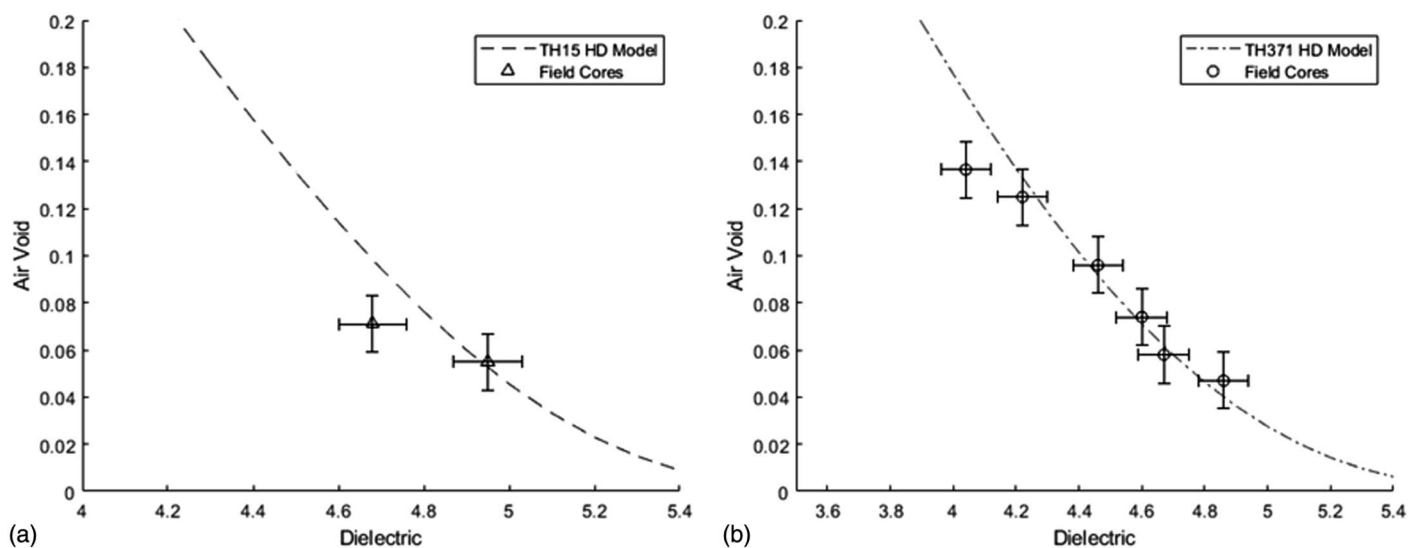


Fig. 1. Deficiency of HD model with fitting field core data: (a) HD model for TH 15; and (b) HD model for TH 371.

cores. All experimental measurements have some expected random errors that can come from, for example, the precision of the equipment being used and testing procedure; therefore, it is important that random fluctuations in the measured values do not drastically change the model fit. Accuracy based on random uncertainty will ensure that specific operators or equipment do not result in completely different assessments of the same pavement. A Monte Carlo simulation is conducted to complete an accuracy assessment (Sokolowski and Banks 2010). A Monte Carlo simulation simulates numerous test scenarios and forecasts the expected outcomes. To explore the accuracy of the empirical models, the measured values of the air void content and dielectric constant for the SGC specimens were randomly varied within the uncertainty range of each measurement. Next, the values were fit with the empirical model, and the percentage of the simulations for which the fit was within the uncertainty of the field validation cores was recorded. The accuracy of a newly proposed model can also be assessed by running the simulation on the empirical models.

Along with Monte Carlo simulations, sensitivity to fluctuations in the mix and parameter sensitivity assessments were conducted. The mix stability was assessed by analyzing two days of paving on the same highway project with an identical target mix design. This scenario is good for testing the stability of the models because quality assurance/quality control (QA/QC) measures are in place to ensure that the actual produced mix does not vary significantly from the target properties (e.g., target 4% air voids at 60 gyrations). Ideally, the fit remains constant within these acceptable mix variation levels. Lastly, parameter sensitivity was assessed to determine whether any unnecessary parameters existed. Additionally, the parameter sensitivity analysis can be used to provide starting values for the parameters. Overall, the combination of these three tests is used to evaluate the proposed MnDOT model. This process is also suggested as useful to determine whether future models can make further improvements over existing empirical models, which will be especially useful as density profiling becomes more widespread because the catalog of available laboratory versus field data that can be used to evaluate the models is increased.

Methodology

Proposed MnDOT Density Model

An assessment of field core data indicates a reduction in the slope at the extreme high and low air void content regions, suggesting that the exponential, linear, and HD models used to convert dielectric values to air void contents do not correctly predict the behavior of the asphalt at the extremes. Fig. 1 indicates that, especially for TH 371, the HD model overpredicts the slope at the high air void content data. The observed behavior indicates an inflection point with flat slopes near the extremes, suggesting that the data may be better represented by a logistic function of the form (Gottschalk and Dunn 2005):

$$y = d + \frac{a}{\left(1 + \left(\frac{x}{c}\right)^b\right)^g} \quad (3)$$

where b , c , and g correspond to adjustments in the slope and inflection point of the logistic function; and d and a correspond to the lower and upper limits of the logistic function, respectively. The logistic function in Eq. (5) was selected because of the observed trend of a decreasing slope at the boundaries of the collected field core data. The parameters in the formula allow for the inflection point and location of these boundaries to be adjusted to the dataset under study. Because the air void content must be nonnegative, the

lower bound of the function, d , was set to zero. Air has a dielectric constant of 1.0006 at normal pressure and temperature (not 1.0 as commonly assumed). For dielectric values close to that of air, the function must approach 100% air voids (Hector and Schultz 1936). Considering these limitations, a second, asymptotic term, $\delta/[(e - 1)]$, was added to the fit. The proposed MnDOT model is of the form

$$AV = \frac{a}{\left(1 + \left(\frac{e}{c}\right)^b\right)^g} + \frac{\delta}{(e - 1)} \quad (4)$$

where AV = air void content; e = measured dielectric constant; and the other parameters are as previously defined. The second portion of the model forces $AV = 100\%$ when $e = 1.0006$. The remaining parameters are obtained through a regression (optimization) conducted with the constraints on e and d .

The parameters can be optimized using Excel's Solver Add-in or another optimization technique, such as MATLAB's `fminsearch` function (MATLAB version 9.7.0.1190202). Additionally, in practice, field hot mix asphalt pavement air void content should not approach 20%. This restriction is valid for hot mix asphalt (HMA) pavements. Any open graded friction courses or porous pavement with extremely high air void content requires modification to the testing method and model. Therefore, the parameter a in the function is set to a value of 0.2, corresponding to the approximate physical limit of the possible air void content measured in an HMA field core. With a constant value of a , the value of δ that forces the fit to be 1.0006 at 100% air void consistently had a value of 0.0008 across more than 50 fits. Because this parameter remained a constant value, it was decided to fix δ at 0.0008. Therefore, the model can be rewritten as

$$AV = \frac{0.20}{\left(1 + \left(\frac{e}{c}\right)^b\right)^g} + \frac{0.0008}{(e - 1)} \quad (5)$$

The remaining three parameters are optimized by minimizing the sum of the square differences between the gyratory puck data and the modeled data. Excel Solver is run with the multistart option enabled to find the global solution independent of the initial guesses for the parameters.

Model Sensitivity Testing

To quantitatively assess the quality of improved models, a stability testing routine is proposed. The procedure begins with a Monte Carlo simulation to assess how the random uncertainty in the air void and dielectric constant of the specimens can influence model stability. The evaluation is made by comparing the 95th percentile confidence windows across the dataset. Next, the variability caused by marginal changes in the mix design is assessed. For this analysis, two or more days of puck data are fit individually, and the fits are compared by calculating the difference between the fits. Again, the 95th percent confidence intervals are compared to assess the depth of the influence that small mix changes have on the model. The final step in the assessment of model viability is the sensitivity of the fit to parameter changes. For this step, each parameter is incremented individually, and the remaining parameters are then refit to the data. Doing so assists in establishing cutoff values and determining whether parameters can be held at a single value to improve computation time.

Monte Carlo Simulation

Because each of the measurements on the pucks has an associated random uncertainty, a Monte Carlo simulation is suggested to

Table 1. Starting values for Monte Carlo simulation

Air void (%)	Dielectric constant
3.29	4.80
3.29	4.80
3.29	4.80
3.29	4.83
3.29	4.83
3.29	4.83
6.53	4.67
6.53	4.67
6.53	4.73
6.60	4.67
6.60	4.67
6.60	4.73
9.63	4.53
9.63	4.53
9.63	4.50
11.69	4.28
11.69	4.23
11.69	4.23
10.40	4.39
10.40	4.45
10.40	4.45

simulate how a model would respond to the innate uncertainty in these measurements. One thousand different simulation sets were conducted using the collected laboratory puck air void contents and dielectric values. For each simulation, the measured values of the dielectric constant and air void content were used as a starting point. The starting dielectric constants and air voids are included in Table 1. Each measured value was allowed to vary by $\pm 1.2\%$ for the air void measurements and ± 0.08 for the dielectric measurement. Each simulation set chose a random value within these experimental value ranges for each of the 21 collected laboratory pucks. The 1,000 sets were then fit to the three models and plotted to display how random uncertainties in the puck measurements influence the spread of fits that the model provides. This simulation gives an idea as to how stable each model is to variations in the individual puck dielectric and air void values. This process is recommended for all future models to assess the stability of the proposed models by comparing the percentage of simulated fits that fall within the uncertainty of the field validation cores. This assessment is valuable because it simulates the randomness that could be expected from any given dielectric or air void measurement. It is important that the proposed model can correctly match the core data (or at least be within reasonable uncertainty of the core data) to enable it to provide a useful dielectric to air void conversion.

The Monte Carlo simulation is intended to simulate variations in air void and dielectric measurements that may be caused by the use of different testing procedures, devices, or operators. The simulations are not intended to suggest a function relating air void change due to a change in mix components.

Mix Sensitivity Assessment

Models of laboratory tested pucks must not vary significantly when the asphalt mix has typical production mix fluctuations throughout the day. Thus, the proposed coreless calibration model should remain stable with slight mix variations to avoid the recalibration requirement every time a small fluctuation occurs. A more stable model reduces the number of recalibrations required for a paving project. Additionally, understanding the influence of mix design changes is useful in suggesting the extent that a mix can be altered

before recalibration is necessary to assure that the fit matches the field data. For a new proposed model, it is suggested that the model be run on several days of test puck data and the fits be compared for the degree to which they vary day-to-day.

Parameter Sensitivity

A sensitivity study was conducted to understand the influence of each of the parameters on the fit quality. The proposed parameter sensitivity analysis fixes the value of one parameter and allows the other parameters to vary while still meeting the constraints for the function (e.g., the dielectric of 100% air must be 1.001). This sensitivity analysis selects one project and fits the specimen data with the fixed values of one parameter to determine the parameter's influence on the quality of the fit. This analysis is only intended to determine the reporting accuracy required for each parameter and whether any of the parameters can be removed to simplify the model and reduce computation time.

Results

The MnDOT model is applied to the data collected from a project on TH 371 in Hackensack, MN. Field cores and the production mix were collected from the project for a coreless calibration and validation of the model fit quality. The uncertainty of the field core measurements is within the acceptable precision range of dielectric measurements of 0.08 [AASHTO PP 98 (AASHTO 2019)] and the Minnesota Department of Transportation core tolerance for bulk specific gravity (G_{mb}) of 0.03 (MnDOT 2018). The uncertainty in the G_{mb} is converted to air void content using the 2.472 maximum specific gravity (G_{mm}) values for the TH 371 production days that correspond to approximately 1.2% air void content. The air void content for the validation field cores was measured using the saturated surface dried method, whereas the laboratory samples were measured using the AASHTO T331 method (AASHTO 2017). The surface dry method has been revealed to underpredict the air void contents due to large, interconnecting voids (Cooley et al. 2002). Cooley et al. (2002) also indicated that the saturated surface dry bias for large air void contents was 0.041 in terms of G_{mb} . This result suggests a reduction in air void contents by approximately 1.6% for the high end of the measured field core data. This value is used to correct the high air void content core during the analysis.

Fig. 2 provides the results from TH 317 project. The traditional exponential model, the HD model, and the proposed MnDOT model are used to fit the puck test results. Additionally, five field cores at random locations were taken to verify the calibration models. The cores were brought to the MnDOT laboratory for a density determination. The exponential model is the most commonly used in practice, but the HD model indicates an improved fit to the experimental data of numerous projects (Hoegh et al. 2018). The HD model well represents the data between approximately 4% and 12% air void content. However, a relatively large deviation from the data exists outside of this air void range. The proposed MnDOT model provides a better fit with the field core data at large air void contents ($>12\%$). For a coreless calibration model to be effective at converting measured dielectric values to air void contents, it needs to be accurate for all expected field data. The incentive structure used by the Minnesota Department of Transportation penalizes pavement that is at high air void contents; therefore, the HD model, which overestimates the slope of the data at high air voids, results in an excessive penalty relative to the actually achieved in-place compaction. For widespread implementation of GPR as a means to assess pavement compaction, it is necessary that the method to

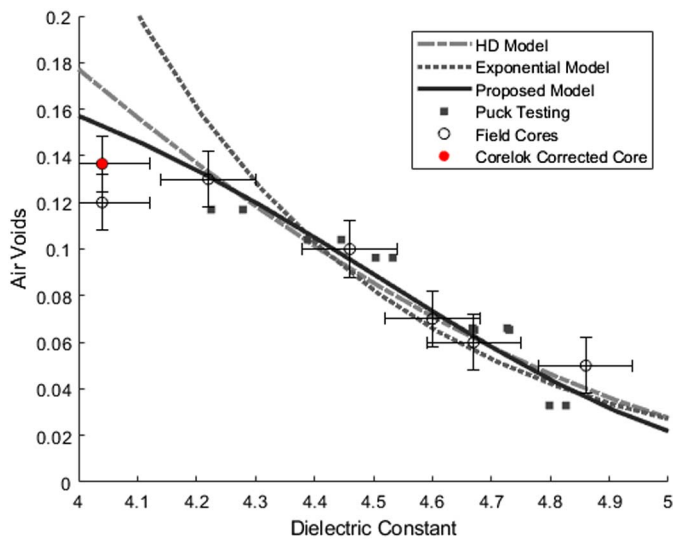


Fig. 2. Comparison of three empirical fits for experimental data collected on highway 371 in Hackensack, MN from October 1, 2019.

convert dielectric to air void is accurate throughout all reasonable air void contents.

Example Using the Proposed Model: Monte Carlo Simulation

The proposed model was compared to the HD model and the traditional exponential model to evaluate their sensitivity to variations in the measured air void and dielectric constant of the pucks. All models were fit using the same 1,000 simulated air void and dielectric values. Fig. 3 provides a comparison between the models and their stability from the expected variation in dielectric and air void measurements. As evident in the figure, the new model has a significantly smaller spread in the high and low dielectric regions, with 0.74% air void variation at a dielectric of 4 relative to 7.59% air void variation for the exponential fit and 3.83% air void variation for the HD model.

Another assessment of the models' quality and stability is the ability of the simulated fits to match the field cores taken on the project. The stability is assessed using the percentage of the 1,000 simulated fits that fall within the uncertainty of the field

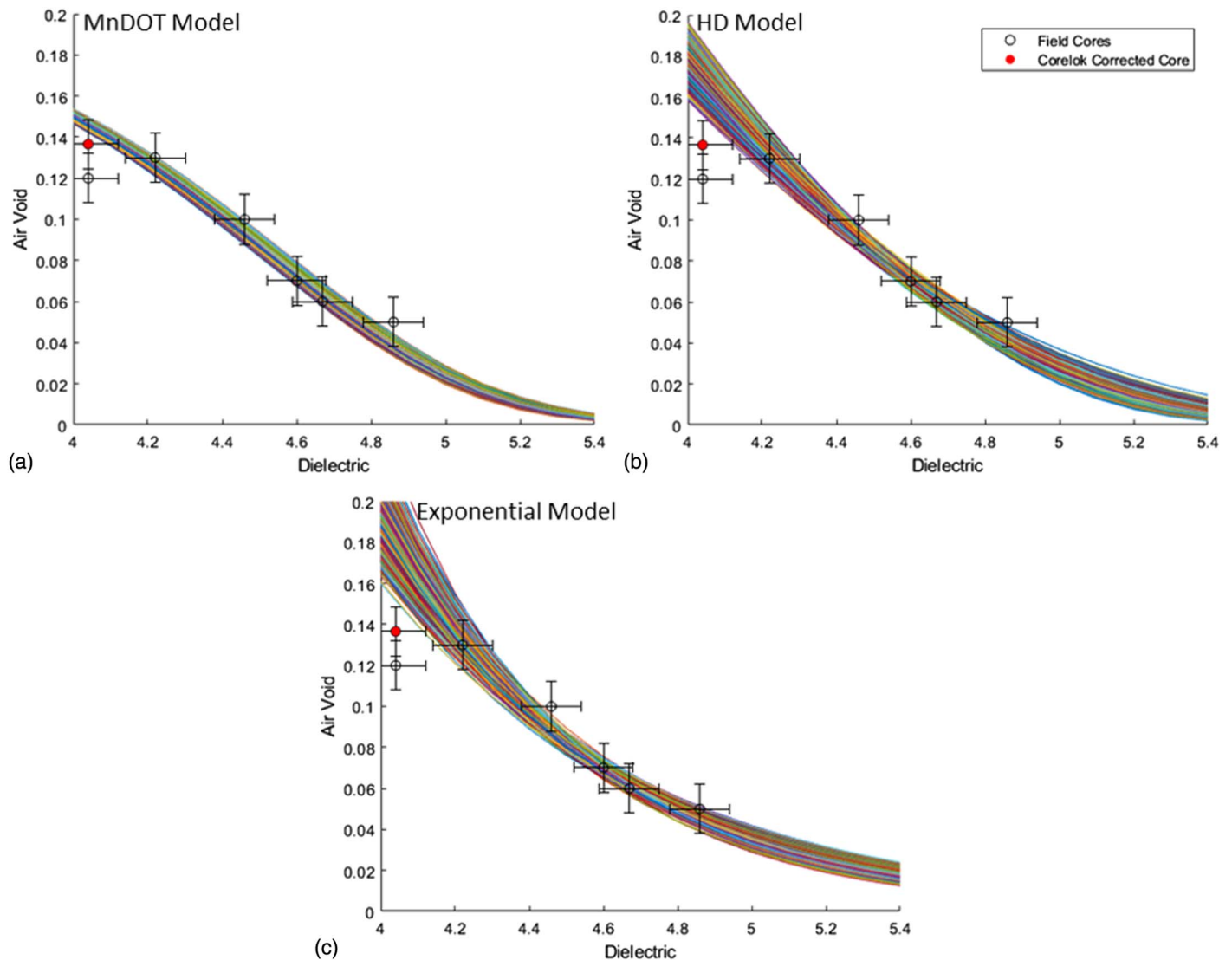


Fig. 3. Comparison of fit stability for Monte Carlo simulation of 1,000 puck dielectric and air void measurements: (a) 1,000 simulated fits for MnDOT model; and (b and c) same simulated results for HD and exponential models, respectively.

cores. Fig. 3 provides the field cores taken on the TH 371 project with their associated measurement uncertainties. All three models correctly fall within the uncertainty of the five higher dielectric cores 100% of the time. However, none of the models are within the lowest dielectric core. As previously stated, because this core likely has an underestimated air void content, the Corelok corrected core is included in the figure (Cooley et al. 2002). When this value is assessed, the three models diverge in their percentage within uncertainty. The MnDOT model has 100% of the fits within the Corelok corrected core, whereas the exponential model has only 21.2% within the core's uncertainty, and the HD model has 29.5%. For this analysis, the percentage of fits falling within the uncertainty of the corrected core (indicated with a solid dot in Fig. 3) can be determined by connecting the ends of the horizontal and vertical error bars. This connection creates a rectangle of uncertainty for the measured field core. All of the fits that fall anywhere within this rectangle are considered to be within the uncertainty of the field core measurement. For the exponential and HD models, only 21.2% and 29.5% of the 1,000 simulated fits are within this rectangle of uncertainty. The Corelok test method is recommended for high air void content cores (Cooley et al. 2002). Therefore, air void content determined from Corelok is a better representation of the true air void content of the core. This analysis indicates that the proposed improved model is a significant improvement over the other two models.

Fig. 3 depicts the results of the Monte Carlo simulation by displaying all 1,000 of the fits created by the method. Whereas Fig. 3 provides a good qualitative view of the improved stability of the MnDOT model, it is also useful to quantitatively assess the spread of values that a random puck variation can cause. The 95th percent confidence interval is reported as twice the standard deviation of the fits at each dielectric value. The assumption that the data have a normal distribution is commonly made when evaluating the quality of the placed asphalt (Breakah et al. 2007). Many agencies use the percent within limits method to evaluate the pavement's quality while also allowing for material variations. This method requires the assumption that the compaction follow a normal distribution. Therefore, the use of twice the standard deviation of the fits for the 95th percent confidence interval is valid. The confidence of each fit across the range of reasonable dielectric values is provided in Fig. 4.

All three models perform to a satisfactory level within the central region of the dielectric range of the pucks. Because the

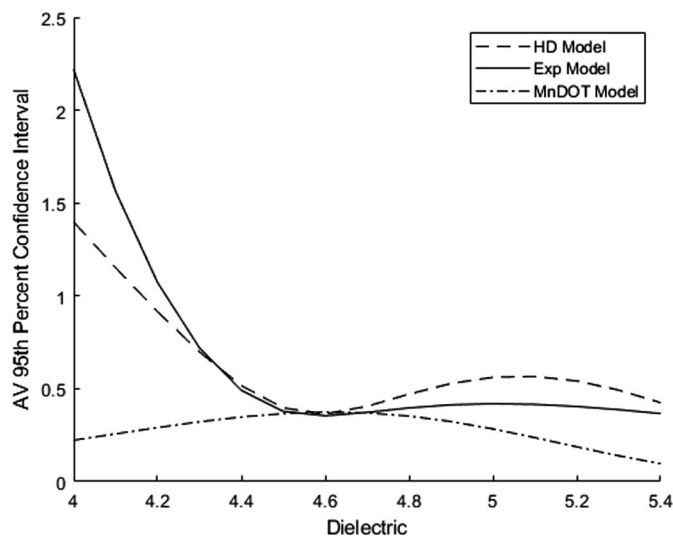


Fig. 4. Ninety-fifth percent confidence interval for Monte Carlo simulation results.

confidence interval is within the uncertainty of the air void measurements, the variation in the fits is small enough that it will have little to no influence on the predicted air voids around this region. At the low end of the reasonable dielectric measurements for the project, the new model has a drastically improved confidence level—on the order of a five times smaller spread. This increase in stability is important because it indicates that the new model is more stable to random uncertainty in the laboratory puck data, particularly for pucks or cores with large air void content. This characteristic is especially critical in assisting the feasibility of widespread implementation of the density profiling method in a field environment in which the number of fabricated asphalt sample pucks used to calibrate the model may be limited.

Example Using the Proposed Model: Mix Sensitivity Assessment

Because the TH 371 project had several days of testing with day-to-day variation in the mix, the models were fit to each testing day and assessed for stability across mixes. The objective is for the fit to match the field core data well without dependence on the day of paving that the laboratory pucks were made. For the TH 371 project, the field cores were taken on October 1 and 6. The results from the laboratory pucks tested on these days were fit to investigate how well the model fits between two days of paving. Fig. 5 displays the models' sensitivity to slight mix changes and other daily fluctuations that could be expected.

Similar to the assessment completed for the puck uncertainty sensitivity, the 95th percent confidence interval is also assessed for changes to the mix design. Fig. 6 depicts the confidence window for the HD and the new models. Again, the new model has improved stability relative to the HD model. A further assessment can be completed by determining the acceptable change in the mix that can still fall within the confidence window to allow the same calibration curve to be used.

Example Using the Proposed Model: Parameter Sensitivity

As previously discussed, the parameter a was fixed to a value of 0.2, corresponding to the maximum expected air void content of a field core. To assess whether this assumption allowed for an

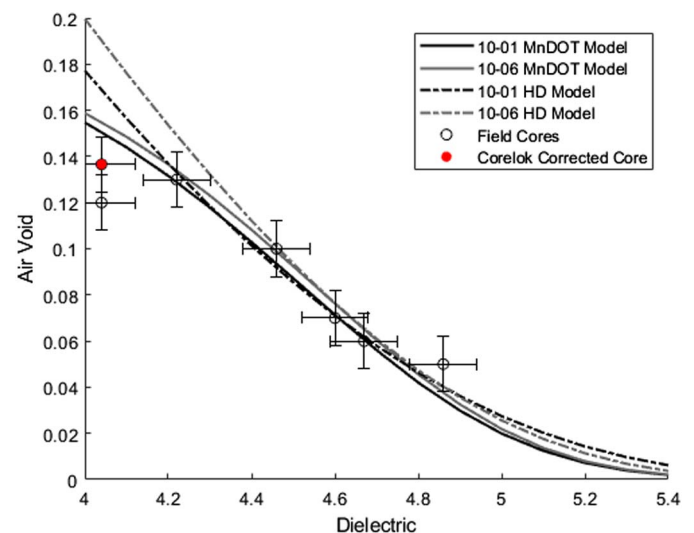


Fig. 5. Model sensitivity to mix design.

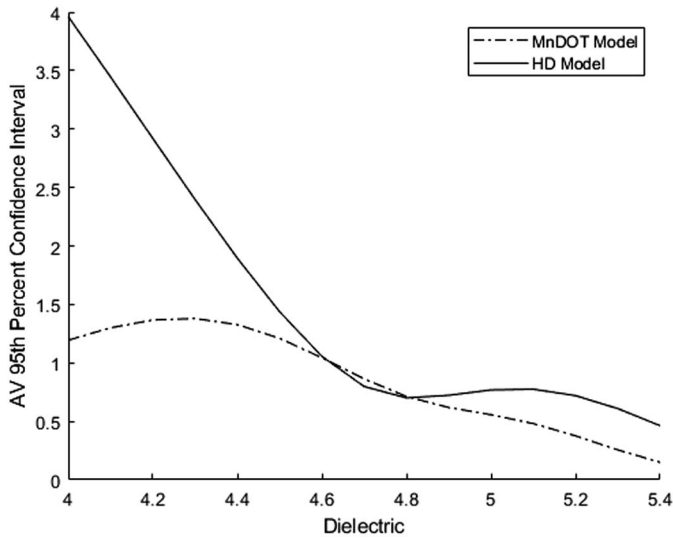


Fig. 6. Ninety-fifth percent confidence interval for HD and new models across four different days of paving.

optimal fit, a was allowed to vary within 0.15–0.5, and the densities obtained from the collected gyratory pucks were used for the regression analysis. The various fits were compared to the collected field core density data. Fig. 7(a) provides the resulting regression curves of various a values. The specific a value of 0.2 is observed to set the upper asymptote of the logistic function. A value that is too low creates excessive curvature that does not fit the trend observed in the cores at the high end of the air void content, and a value that is too high increases the slope of the fit at the low dielectric region, fitting the data poorly.

A similar assessment was completed for the remaining parameters. Figs. 7(b–d) indicate all of the remaining parameters and the fits resulting from fixing each parameter at a specific value when a is set to 0.2. One of the most important trends that is evident from this analysis is that the parameter g can be varied significantly, and the other parameters adjust to result in an insignificant amount of variation in the fit, as indicated in Fig. 7(d) by the small change in the fit caused by three orders of magnitude change in g . This result suggests that the data could be fit without changing the value of g . Because fixing the value of g results in a slight increase in the sum

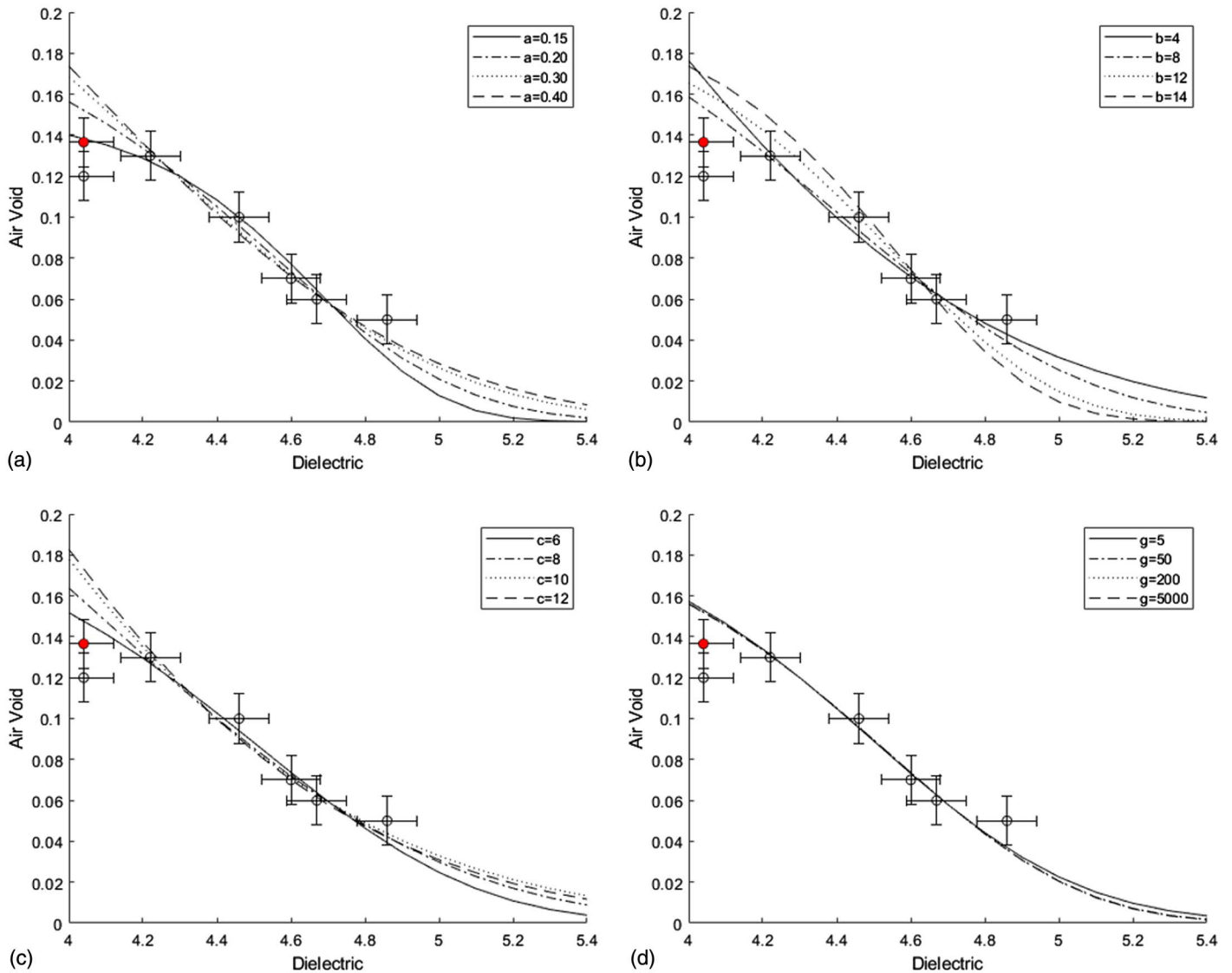


Fig. 7. Plots depicting various fits of gyratory puck data at fixed values of four of the fit parameters: (a–d) sensitivity of the MnDOT model to parameters a , b , c , and g .

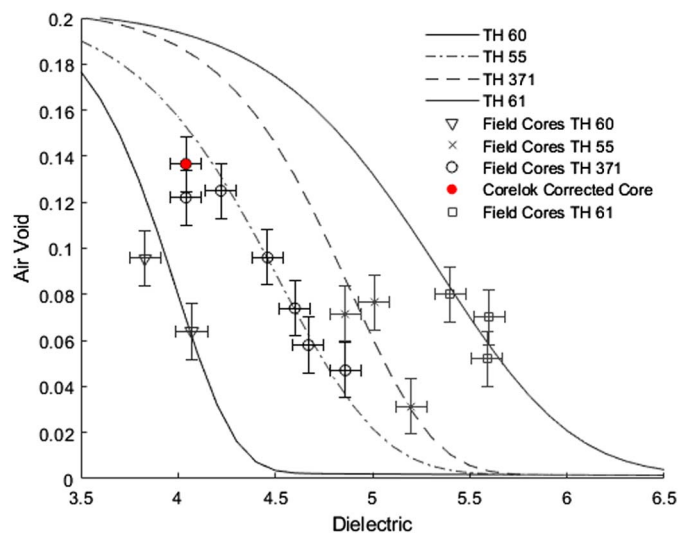


Fig. 8. Proposed model fits for TH 371, TH 55, TH 60, and TH 61.

of the difference of squares for the data set, the optimal solution is still found by allowing g to vary.

Unlike g , the parameter c plays a significant role in the quality of the fit. The parameter c increases the slope of the fit and can result in the overestimation of the pavement's air void content for low dielectric values.

The range of values presented in this analysis should offer reasonable starting points (or initial guesses) that are required to complete the parameter optimization. However, important to note is that the parameters can vary among mix designs; therefore, a specific mix design may exist that results in parameters exceeding the expected range.

Model Verification on Multiple Projects

To confirm that the proposed model is not uniquely suited for the chosen highway, TH 371, the ability of the new, improved MnDOT model was used to match field cores collected on TH 60, TH 55, and TH 61. Because the four selected projects have significantly different mix designs and aggregate sources, the model is tested to determine whether it can remain flexible enough to handle various asphalt mixes. For brevity, only the two majority aggregate sources are listed for each project. The remaining aggregate sources are available on request. TH 371 has the mix designation SPWEA340C with a ½-inch maximum aggregate size and PG 58-34 binder. The majority aggregate source components were 30% Powers BA Sand and 22% Powers ½ Rock. TH 60 uses mix designation SPWEB440 with a ¾-inch maximum aggregate size and PG 58H-28 (MSCR) binder. The majority source components were 33% SRP WMS (36) and 21% SRP ¾ DF (18). TH 55 has mix designation SPWEA340 with a ½-inch maximum aggregate size and PG 58-34 binder. The majority source components were 29% Naak Nat Fine 3A-BA19-0029 and 22% Naak Washed Cr. Fines 3A-BA19-0028. TH 61 uses mix SPWEB440 with a ¾-inch maximum aggregate size and PG 58S-28 (MSCR) binder. The majority source components were 38% Doane ¾ Bit Rock and 34% Doane Man Sand.

Although the mix components and specific mix designs are included in this paper, important to note is that the calibration methodology accounts for the aggregate dielectric properties as part of the bulk production mix from the specific day of paving during which DPS data were collected. Based on the results indicated in Fig. 8, the regression curves on the three projects correspond very well to the field core density results. The predictions are within

the uncertainty of the collected field cores, suggesting that the model improves on the current state-of-the-art models and is applicable to more than just the TH 371 project.

Conclusion

A new model is proposed to establish a calibration relationship between the dielectric measurement and the field HMA compaction density. The MnDOT model improves on the exponential and HD models in its ability to correctly convert collected GPR field data to in-place air voids, especially at the extremes. The incentive structure used by the Minnesota Department of Transportation (and many other state departments of transportation) penalizes pavement that is at high air void contents; therefore, the HD model, which overestimates the slope of the data at high air voids, could result in an excessive penalty relative to the actually achieved in-place compaction. The increased accuracy of the MnDOT model reduces the misrepresentation of the actual pavement compaction. Improvements to the new model were evaluated and verified using a novel statistical analysis procedure. The statistical approach employed Monte Carlo simulations to assess the variability in the fit that can occur due to slight fluctuations in the measured puck values. This assessment indicates that the MnDOT model falls within the expected uncertainty of all of the field cores (after correcting the highest air void content core for the saturated surface dry method), whereas the HD model only falls within 29.5% of the time. Additionally, the assessment of the spread of the Monte Carlo simulated fits indicates that the MnDOT fit has the least variation across all expected field air void content ranges. Next, the models are tested across the same asphalt mix design on different production days to determine whether a slight variation in the mix makes the conversion no longer useful. This analysis also indicates improved stability for the MnDOT model compared with the HD model. Field core validation results indicated that the stability of the MnDOT model allowed for accurate prediction of in-place air voids even when the mix from a different production day was used to convert the GPR collected data to air voids. The final step in the model testing procedure is to determine the sensitivity of the models to their parameters. This step verifies that all parameters are necessary and contribute to the quality of the fit that is created. This complete testing procedure confirms that the MnDOT model is a better tool for use in the coreless calibration of collected GPR data to air void contents than the currently available models. The techniques used to complete this assessment can also be employed to assess future proposed models or the magnitude of the mix design change required to recalibrate the conversion using SGC specimens.

Future research efforts will focus on obtaining more of the high and low air void content field cores to further verify the improvements made by the MnDOT model. The assessment presented in this report was supported by only three field cores at the extremes of the measured air void content. Thus, future work will attempt to sample more cores with greater than 12% air void content and less than 4% air void content. For the high air void content cores, field cores can be taken from low compaction regions, such as pavement on road shoulders. On the other extreme, the real-time display of the DPS can be used to identify regions with very high compaction for coring.

Data Availability Statement

All of the data, models, or code generated or used during the study are available from the corresponding author by request, including

the Microsoft Excel macros to run the fit optimization and the MATLAB code to create the Monte Carlo simulations and visualize the results.

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