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Sensitivity Analysis of 2002 Design Guide
Distress Prediction Models for Jointed Plain Concrete Pavement

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The AASHO 2002 design guide was calibrated with Long-Term Pavement Performance (LTPP) data collected throughout the United States. The model parameters were tested to identify any problems in the software. Sensitivity analysis helps in identifying the most important variables in the models and variables for which reasonable assumptions can be made without a significant change in the predicted performance.

The significance of the sensitivity analysis is acute for California because of the state’s need for revision of highway design procedures in the state. The models and variables with which reasonable assumptions can be made without a significant change in the predicted performance are.

The limitations of the empirical procedures based on the AASHO Road Test led the AASHO 2002 Task Force on Pavements to take the initiative to develop a new pavement design tool based on mechanistic-empirical (ME) principles. The resulting pavement design procedure, called the 2002 Design Guide (2002DG in this paper), is intended to be user-friendly software for design of new and rehabilitated flexible, rigid, and composite pavements. The models in the design guide were calibrated with data from Long-Term Pavement Performance (LTPP) projects across the United States. However, very few sections in California were used for the calibration, which led to a need to check the model’s predictions for California conditions. Also, AASHO recommends that each state validate and, if necessary, recalibrate the models with climatic, traffic, and environmental data representative of that state. For California, this process consists of three steps:

- Benchmarking or sensitivity analysis
- Validation with accelerated pavement testing data
- Validation with field data

The first step of the validation process is reported on here, which is the sensitivity analysis of the jointed plain concrete pavement (JPCP) module of the software. Sensitivity analysis helps to check the robustness of the model predictions, identify key inputs for the design process, and identify any problems in the software. A positive outcome from the sensitivity analysis is a prerequisite to the expensive and time-consuming validation process with field data because the sensitivity analysis identifies important variables in the models and variables for which reasonable assumptions can be made without a significant change in the predicted performance.

The significance of the sensitivity analysis is acute for California because of the state’s need for revision of highway design procedures in the state, which presents the opportunity to immediately incorporate findings from the sensitivity analysis. Some sensitivity analyses have already been made. Hall and Beam (1) looked at the sensitivity of the models to different input variables. However, one major limitation of that study is that only one variable is changed at a time compared with the baseline case, resulting in very few cases and failure to capture the interactions among the variables. Mafell et al. (2) studied the sensitivity of the models to the coefficient of thermal expansion. Khaznovich et al. (3) studied the sensitivity of the models to the coefficient of thermal expansion. Khaznovich et al. (3) studied the sensitivity of the models to the coefficient of thermal expansion. Khaznovich et al. (3) studied the sensitivity of the models to the coefficient of thermal expansion.

The 2002DG user’s manual discusses sensitivity of the models to some variables but misses some key variables such as traffic volume, axle load distribution, and subgrade type. In the current study, about 10,000 runs are analyzed, and this large number of runs enables the study to evaluate variable interactions as well as single effects for the full range of parameters anticipated in California.

FULL FACTORIAL EXPERIMENTAL DESIGN

The variables and factor levels in the full factorial experimental design are as follows:

- Axle load spectra: rural and urban
- Traffic volume: traffic intensity (TH) of 12, 15, and 18
- Climatic regions: South Coast (Los Angeles), Valley (Sacramento), and Mountain and High Desert (Reno)
- Pavement concrete (PCC) thicknesses: 7, 8.5, 9, 12, and 13 in. (since the software operates only with customary English units, customary units are also used to report the inputs and outputs of the software)

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• Tires: asphalt concrete base and cement-treated base.
• Surfacing: high-alkali clay and poorly graded sand.
• Driveway: no driveways.
• Shoulder type: asphalt shoulders, filter shoulders, and widened truck lane.
• Joint spacing: 15 and 19 ft.
• PCC flexural strength at 28 days: 625 and 700 psi.

This testicular result in 8,640 cases. To the extent possible, the inputs for all the variables used in the sensitivity study are chosen to represent the practice and conditions in California. All cases were run with a reliability level of 50% and a design life of 30 years.

INPUTS
Traffic Inputs
California has a well-developed traffic database with input from about 100 vehicular-movement (VWM) stations in the state. Most of the traffic inputs are derived from the WIM traffic database (13). WIM data from two types of locations, urban and rural, were used in the study. Urban locations are defined as freeway segments that have more than 550 trucks than Class-A trucks, and rural locations have more Class-A trucks. Class-A trucks are more with short-travel typically used for short-haul distribution, and Class-A trucks have long trailers typically used for long-haul.

The three traffic-volumed used are 11, 22, and 56 million, respectively. Each TF for the factorial experiment was calculated twice, once by using an example urban axle load spectrum from the WIM database and again by using the rural spectrum. The number of trucks was adjusted for each case to obtain the desired number of EILS by using a 1.2 expanded pro the practice at the California Department of Transportation (Caltrans) for each spectrum. Hourly truck distribution factors, vehicle class distribution factors, and monthly adjustment factors were obtained from the WIM database. Zero growth rate was assumed for simplicity. This assumption does not affect the results much because the bias for load is used for damage and vulnerability to the distress predictions model, which assumes a linear damage rate with traffic repetitions. The only sensitivity of the results would be due to PCC strength degradation. The normalized axle load distribution used in this study were determined from the WIM data. Urban and rural locations have significantly different axle load distributions.

Climate Inputs
The three climate regions included in the sensitivity analysis are South Coast (Los Angeles), Valley (Sacramento), and Mountain and High Desert (Reno). The South Coast is characterized by mild temperatures, little temperature change from day to night, and low rainfall. The Valley region has hot summers, cool winters, large day-to-night temperature changes, and moderate rainfall. The Mountain and High Desert region is characterized by hot summers, cold winters, and moderate rainfall (6).

Design Features
Different combinations of joint spacing, shoulder type, and load transfer efficiency are constructed from the factorial. For dowelled

pavements, the element of the dowels is 1.5 in. and the dowel spacing is 12 in. The pavement curl-up was effective to temperature difference is assumed to be -10°F, which was fixed in the LLTP calibration by the (2002E4) team. It is assumed that there is no bending between the base and the PCC slab. The modulus index of the base is assumed to be 3, meaning that the base material is in tension regime.

Surface and Drainage Properties
The default value used in the software for surface drainage absorptivity is 0.05, and this value was fixed for calibrating the models in the software. However, in this study surface drainage absorptivity assumed to be 0.05, which was measured by the Lawrence Berkeley National Laboratory (7) for new rigid pavements. Default values are used for drainage parameters.

Payment Structure
The pavement structure analyzed has a PCC slab of varying thickness (7, 8, 9, 10, or 12 in.), 6-in. cement concrete base (CCB) or asphalt concrete base (ACB), and 6 in. of aggregate subbase and high-alkali clay (HCC) or gravel subgrade (SP) subgrade. The concrete or base used by Caltrans is characterized as CCB in this paper.

Material Properties
The values used for PCC material properties are typical values used by Caltrans. Votatility used for 38-day, flexural strength are 625 psi and 700 psi. Flexural strength of 625 psi was obtained from a mix used for paving in Los Angeles, California, and meets the Caltrans specification. The thickness was chosen to be about 12% more than 625 psi. The same mix design parameters were used for both flexural strength cases. Default values were used for CCB and the unbound layers.

RESULTS AND ANALYSIS
The software was run for all 8,640 combinations in batch mode, for which the cracking and the finding models need to be run separately. After the finishing and cracking "analysis were determined, empirical equations mentioned in the design guide's user's manual were used to estimate spacing and internal weightings index (10). The sensitivity maps were made with a deflux version, but only the results for some of the cases were compared with the current version. The comparison showed that there were no significant changes in the current version. The results from the cases that permitted identification of the effect of various variables on cracking, transverse cracking, and HII. The effects of different variables are summarized in the form of box plots and discussed in the following sections. The four horizontal lines in a box plot represent maximum, 25th percentile, 50th percentile, and 75th percentile, and maximum values present in the data.

Effect on Transverse Cracking
The results showed that joint spacing, PCC thickness, climate region, traffic volume, and dowel type have a significant impact on transverse cracking. Basalt type, subgrade type, and axle load spectrum for
a fixed number of ESALs do not affect transverse cracking as much.

The following effects were found:

- As the traffic volume increases, predicted cracking increases (Figure 1a).
- As the thickness of the PCC slab increases, the amount of cracking observed in the pavement decreases (Figure 1b).
- The models predict the least cracking for the South Coast climate followed by the Mountain climate. The Valley climate has the highest amount of cracking (Figure 1c).
- Joint spacing is the key variable that controls transverse cracking. The results from the sensitivity analysis show a dramatic difference in cracking between structures with joint spacing of 19 in versus 15 ft. Joint spacing of 19 in is very detrimental to the pavement. Figure 1d summarizes the effect of joint spacing. These findings match the experience in California, where repeated joint spacing of 12, 13, 18, and 19 ft has been used for many years.

- Pavement structure with a widened truck lane appear to perform better than those with tied shoulders or asphalt shoulders. Widened truck lanes reduce cracking considerably (Figure 1e).
- There are cases with widened truck lanes that show 100% cracking. This situation occurs because other inputs such as very high traffic loading in Valley or Mountain regions with joint spacing of 19 ft and 7-in. slab thickness dominate the expected performance.
- The results from the sensitivity analysis show that, on average, subgrade type has little effect on cracking (Figure 1f).
- Base type does not have much effect on cracking. Though on average CTB performs better than ACB, these are almost equal, with 100% of cases in which CTB performs better than ACB and ACB performs better than CTB.
- The flexural strength of PCC does not have much effect on transverse cracking, according to the model.
- Axle load spectrum has little effect on cracking. When the axle load distribution is changed, the other traffic characteristics associated with that location, such as vehicle class distribution, have...
traffic distribution, and annual average daily truck traffic, also change. Plausible reasons for the lack of significant effects are that

- The other traffic inputs are changed along with the spectrum, and
- TI, which is used to quantify the traffic volume, captures the effect of the spectrum fairly well.

Figure 3 summarizes the effects of all the variables on transverse cracking and their relative importance in controlling cracking. The plots show the average amount of cracking for each factor level of all the variables. Among the variables that a designer can control, joint spacing and shoulder type are significant, and have already been dealt with in recent Caltrans practice. In general, model predictions for different factor levels of all the variables agree with prevailing knowledge in pavement engineering. However, there are some exceptions, which are presented later in the paper.

**Effect on Faulting**

Results showed the following effects on faulting:

- The most important factor that causes faulting is load, whose 10 magnitude effect on faulting is shown in Figure 3c; there is hardly any structure with dowels that have fault heights greater than 0.1 in.

![Figure 3c: Effect of load on faulting](image)

**Effect on RII**

The variables that affect the RII most are the same ones that affect faulting and cracking significantly. So, dowels, traffic volume, joint spacing, PCC thickness, climatic zone, and shoulder type have a significant effect on RII. However, treated base type, subgrade type, and strength of PCC have little effect on RII according to the models. Figure 3 summarizes the relative importance of all the variables on RII.

**Effect of Coefficient of Thermal Expansion on Rigid Pavement Performance**

Coefficient of thermal expansion (COTE) was not included in the sensitivity study initially. However, a separate sensitivity study was performed in order to check the sensitivity of cracking and faulting models to COTE. A robust of the full factorial model for the primary sensitivity study was run with two different COTE values (4 x 10^-6/°F and 3 x 10^-6/°F). The factorial consisted of 2 x 2 x 3 x 2 x 2 x 2 x 2 x 2 x 2 x 2. The thickness of PCC (9 and 12 in.), shoulder type (asphalt, red, and widened w/drain), climatic zone (South Coast, Valley, and Mountain), exposed and covered condition with TI of 16, 18 IP subgrade, and CTB. COTE of 4 x 10^-6/°F corresponds to PCC with limestone or granite aggregate and COTE of 3 x 10^-6/°F corresponds to PCC with quartzite, chert, and gravel. Crystalline, gravel, and quartzite are the most commonly used aggregate types in California. All the cases were run at a reliability level of 5% and 10-year design life. Figure 3 summarizes the effect of COTE on cracking and faulting. It can be seen that COTE significantly affects transverse cracking. The effect on faulting is minimal. The sensitivity of these results will be checked during subsequent field validation of the models. If the results are found to be in sensitive the model suggests, the specification of COTE or design for a site-specific COTE will need to be considered by Caltrans.

**Effect of Shortwave Surface Absorptivity**

Surface absorptivity (SA) is defined as the amount of solar radiation absorbed by the pavement surface. Although this variable was not included in the full factorial sensitivity study, it was found that the cracking model is highly sensitive to SA. A separate experimental design was run to understand the sensitivity of the 20GDD models.
This variable. The new experimental design was similar to the one used for the sensitivity study but with fewer variables. The factorial consisted of axle load spacing (urban and rural), traffic volume (TI of 12 and 14), PCC thickness (6, 10, and 12 in.), base type (CTB and AC-9), shoulder type (surf rock, split, and wideload truck lane), and joint spacing (15 and 30 ft). Two different values of SA, 0.65 and 0.85, were used. The models in the 2002DG software were calibrated with a fixed SA value of 0.85, and it was not measured on the calibration sections. In the main sensitivity analysis, SA was assumed to be 0.65 (more reflective than 0.85), a typical value for new PCC pavements. The analysis included the desert climate, SP subgrade, and PCC thickness of 625 mil. All the cases were run at a reliability level of 50% and for a 30-year design life.

In some cases there is a significant difference in cracking even when every other factor is the same except SA. In some cases cracking increased by as much as 17 times when the SA was changed from 0.65 to 0.85. Figure 7a shows a case in which there is a significant increase in cracking due to change in the SA value. The input corresponding to this case are urban area, 15-ft joint spacing, widened truck lane, CTB, and 8-in. PCC slab. A closer look at 6b results from this secondary sensitivity study revealed that thinner slabs were more affected by SA than thicker slabs. Figure 7b shows the effect of SA on cracking in comparison with other key variables. It can be seen that according to the 2002DG models, SA is as important as traffic volume and shoulder type in its impact on transverse cracking. This result will also need to be verified to be extent possible during field calibration. Currently, key differences in SA are included in the form of the models. SA does affect cracking, but the impact is not very significant. In the study by Hult and Beamer, they found that SA was sensitive for cracking and insensitive for faulting (1).

**ANOMALIES**

**Thickness of Slab**

There are cases in which thinner pavement structures perform better than thicker pavement structures.
- PCC flexural strength at 28 days of 626 psi, and
- Widened truck lane.

In about 155 cases 9-in. slabs have more faulting than 8-in. slabs, with a maximum difference in faulting of 0.004 in. There are no inputs common to these 155 cases, but most of them have 19-ft joint spacing.

**Structures with 9-in. Slab Better Than Structures with 10-in. Slab**

There are 12 cases in which 9-in. slabs perform better than 10-in. slabs, with the maximum difference in proportion of slabs cracked being 19%. The inputs common to these 12 cases are:
- CH subgrade,
- Mountain climate zone, and
- PCC flexural strength at 28 days of 626 psi.

There are 461 cases in which 10-in. slabs have more faulting than 9-in. slabs and the maximum difference in faulting is 0.008 in. The only input common to these 461 cases is that all of them have arrow.

**Structures with 10-in. Slab Better Than Structures with 12-in. Slab**

There are 419 cases in which 10-in. slabs have less faulting than 12-in. slabs, with a maximum difference in faulting of 0.064 in. The structures corresponding to all these cases have arrow. There are no cases in which 10-in. slabs perform better than 12-in. slabs in terms of percent of slab cracked.

**Shoulder Type**

Most cases in the sensitivity study show that widened truck lanes perform better than tie shoulds, which in turn perform better than asphalt shoulders. This finding makes sense. However, some cases do not show this performance.

**Asphalt Shoulders Better Than Tie Shoulders**

In 18 cases in the study, structures with asphalt shoulders are better than those with tied shoulders. The maximum difference in proportion of slabs cracked is 24.4%. Inputs common to all these cases are:
- CH subgrade,
- Mountain climate zone, and
- PCC flexural strength at 28 days of 526 psi.

There is only one case of structures with asphalt shoulders with less than 10-in. slabs and the difference in faulting is 0.3282 in.

**Asphalt Shoulders Better Than Widened Truck Lanes**

In six cases structures with asphalt shoulders have less cracking than structures with widened truck lanes, with the maximum difference in the proportion of slabs cracked being 12.5%. All cases have CH
Tied Shoulders Better Than Widened Truck Lanes:

In eight cases structures with tied shoulders performed better than structures with widened truck lanes in terms of cracking. The maximum difference in proportion of slabs cracked is 33.1%. The inputs common to these eight cases are CH subgrade, 12-in. thick slabs, rural spectrum, and Mountain climate zone. There are no cases of tied shoulders performing better than widened truck lanes in terms of faulting.

Subgrade Type

Poorly graded sand (SP) is 80% and less erodible than high-plasticity clay (CH), so SP is naively supposed to be associated with better pavement performance than CH in terms of faulting and cracking. However, there are 2,644 cases in which structures with CH subgrade are predicted to have less cracking than structures with SP subgrade. There are no inputs consistent among these 2,644 cases, but most of them are in the Mountain climate zone. The difference in proportion of slabs cracked grew as high as 80% in some cases.
but such cases are few. On average there is not much difference in cracking performance between the two subgrade types used in this study. Intuitively, the softer subgrade should potentially provide lower cutting stresses under nighttime temperature gradients and moisture gradients because the layers underlying the slab accommodate more to the slab shape.

There are 735 cases of structures with SP subgrade that have more faulting than those with CH subgrade, with a maximum difference in faulting of 0.16 in. There are no inputs common to these 735 cases. There are no intuitive reasons why the more erodible CH subgrade should provide better performance than the SP subgrade.

To understand better the effect of subgrade type on rigid pavement performance, another small sensitivity analysis was performed. Four subgrade types having Unified Soil Surface Classifications of GW, SP, CL, and CH were analyzed for two thicknesses of PCC slabs (9 in. and 12 in.) over 6 in. of CTB and 6 in. of aggregate subbase. The other key inputs used were rural spectrum, traffic of 225 million ESALs (TI = 17), Valley climate, COTE of 5.5 x 10^-9°F, 15-ft joint spacing, and surface absorptivity of 0.65. The faulting, transverse cracking, and IRI values for different cases at the end of a 30-year design life and 50% reliability are shown in Table 1. The assumed resilient modulus and the corresponding k-value estimated by the software for the four soil types are shown in Table 1. The estimated k-values are much higher for sand and gravel subgrades than those encountered in the field.

Results show that a softer subgrade results in less faulting when dowels are not used. In all cases softer subgrade helps in reducing transverse cracking. This finding would lead a designer to be more concerned with faulting for unskewered pavements for well-graded gravel subgrades than for high-plasticity clay subgrades, which is not reasonable. To understand the reason behind this anomaly, the faulting model used in the design guide was examined (1). According to the model, faulting is directly proportional to the differential energy (DE), which in turn is a function of corner deflections. A three-dimension finite element analysis tool, EverFE, was used to calculate the deflections at the corner of a single slab, and the DE was estimated. According to EverFE, as the stiffness of the subgrade increases, the DE decreases and so faulting is supposed to decrease. However, in the 2002, the DE increases as the stiffness of the subgrade increases. The reasons for this difference are not known.

**Subbase**

A few cases were run to see the effect of granular subbase under CTB. The results showed that the thickness of granular subbase had no effect on rigid pavement performance. When 6-in. granular subbase was used, the faulting, cracking, and IRI values obtained were 0.478 in., 96.7%, and 394 in./mil and when 7-in. subbase or no subbase was used, almost same results were obtained.
<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>Performance of Structures with Different Soil Types</th>
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<tbody>
<tr>
<td>Soil Type</td>
<td>M (psi)</td>
</tr>
<tr>
<td>Ne-dwells</td>
<td></td>
</tr>
<tr>
<td>GW</td>
<td>40,000</td>
</tr>
<tr>
<td>SP</td>
<td>28,000</td>
</tr>
<tr>
<td>CL</td>
<td>16,000</td>
</tr>
<tr>
<td>CH</td>
<td>8,000</td>
</tr>
<tr>
<td>Dwells</td>
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<tr>
<td>GW</td>
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<td>SP</td>
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<td>8,000</td>
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<td>CH</td>
<td>5,000</td>
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<td>CH</td>
<td>1,000</td>
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<tr>
<td>CH</td>
<td>500</td>
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*Approximate dynamic k-value estimated by the software from the M, k-value.

These results assumed SP subgrade and undowelled pavements. Similar results were obtained for CH subgrade and dowelled pavements. From these results it can be said that according to the models, the PCC slab and C/STB layer can be constructed directly above high-plasticity clay without affecting the performance of the pavement, which is not reasonable. Current California practice of placing an aggregate subbase under the treated base on clay and silt subgrades and placing the treated base directly on sand and gravel subgrades will be recommended for use with other results from the 2002DG software.

SOFTWARE PROBLEMS

Inability to Produce Results

For some projects it was found that two input files containing the same data produced totally different outputs. There are few cases in which this problem was detected, and such cases showed unreasonable results such as 0% cracking for 7-uk slabs with 0-8 joint spacing under very high traffic volume. When such cases were rerun with the same input data, they gave different results, which were reasonable.

Aggregate Type

The type of aggregate is a redundant input since it does not affect the calculation of distress. When aggregate type is changed, the COTE of PCC is not changed automatically and must be changed manually.

Climate Data

There are some major California weather stations that are not on the list of weather stations for which the software has climate data, and some stations on the software’s list do not have more than 2 years’ worth of data. If chosen, some weather stations on the software’s list result in errors, and the program crashes.

CONCLUSIONS

The sensitivity analysis done as part of this study helped to identify the basic behavior of the models and to identify some flaws in the 2002DG models and the software. The following conclusions are drawn from the study:

- On average, both the cracking and peaking models show trends that agree with prevailing knowledge in pavement engineering, with a few notable exceptions.
- Anomalies occurred for a limited number of cases, applicable to both transverse cracking and peaking models:
  - Thinner pavement structures performed better than thicker pavement structures,
  - Structures with asphalt shoulders performed better than structures with tied shoulders and widened truck lanes, and
  - Structures on softer subgrade performed better than structures on stiffer subgrades.
- Surface absorptivity (SA) is predictive of an unreasonably large effect on cracking performance in some cases.
- Subgrade k-value in many cases is unusually high when a stiffer subgrade is used. This finding suggests there may be some flaws in the k->e conversion model used in the software.
- The sensitivity to subgrade type is counterintuitive and can lead to probably dangerous situations for inexperienced designers. It is recommended that local experience be used in the decision of whether to use aggregate subbases and that the model needs better calibration with regard to subgrade type.
- Inability to reproduce the results can confound the credibility of model predictions, which is a software bug.
- Some major weather stations in California are not included in the climate database built into the software. Some of the climate files are corrupt and cause the software to crash.
- PCC properties like COTE are not changed automatically when the user changes aggregate type, making it a redundant variable.

Overall, the PCC module of the 2002DG produces reasonable predictions of pavement performance. However, the accuracy of the predictions needs to be validated by using field data in California.
2002DG needs to be used for pavement design, it should be used with some caution, keeping in mind the anomalies mentioned here. The designer should be careful in selecting input values for SA and COTI and in using results for different subgrade types and should apply good judgment when selecting whether to use subbases because the models seem to fail to capture the effect of granular base and subgrade accurately.

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