Temperature Estimation for Low-Temperature Cracking of Asphalt Concrete

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Pavement temperature prediction is an important step in the modeling of pavement performance. Several computer programs for estimating asphalt concrete pavement temperatures were evaluated. Results from the FHWA integrated model were compared with actual recorded pavement temperatures. Results from the integrated model were also compared with those of other temperature prediction models, computations of low-temperature damage (COLD) and THERM. Finally, a two-dimensional finite element model was used to evaluate the importance of pavement edge effects. Pavement temperatures predicted by the FHWA integrated model compared more realistically with actual temperatures than did the temperatures predicted by other available models. The effect of neglecting edge effects is not significant for typical pavement cross sections but may be important for shoulders and for extreme cross sections.

Consideration of environment-related distresses of asphalt concrete, including low-temperature cracking, must play a major role in developing performance-based specifications. Low-temperature distress of asphalt concrete pavements is manifested by transverse cracking—cracks perpendicular to the direction of traffic and spaced from several feet to several hundred feet apart. Block cracking, in which transverse and longitudinal cracks divide the pavement into blocks, and some longitudinal cracking are also manifestations of low-temperature cracking.

Three factors are considered the most likely instigators of low-temperature cracking: extreme temperatures, repeated cycling of temperature changes, and cooling rates within the pavement. Temperature cycling, even in relatively moderate climates, may lead to exceeding the asphalt concrete's fatigue resistance and the occurrence of thermal-fatigue, low-temperature cracking. The quicker the rate of cooling, the greater the thermal stresses within the pavement and the more likely a pavement will experience fatigue as a result of temperature cycling. Modeling of low-temperature pavement performance must incorporate a method of modeling the environment and predicting pavement temperatures.

An extensive review of pavement temperature prediction methods was conducted. The FHWA integrated model was evaluated as the most comprehensive model available and was therefore compared with actual pavement temperatures and with other available models. In addition, the possible error induced by using a one-dimensional model that ignores edge effects was evaluated.

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OVERVIEW OF FHWA INTEGRATED MODEL

The FHWA integrated model was developed for FHWA's Office of Engineering and Highway Operations Research and Development by the Texas Transportation Institute (TTI), Texas A&M University. The program attempts to model accurately enough for design purposes such important climatic factors as temperature, rainfall, wind speed, and solar radiation. The result is "meaningful simulations of the behavior of pavement materials and of subgrade conditions over several years of operation" (*1*, p. 1).

The FHWA integrated model of the climatic effects on pavements consists of four main parts. These are the precipitation model (Precip model), the infiltration and drainage model (ID model), the climatic-materials-structural model (CMS model), and the Cold Regions Research and Engineering Laboratory frost heave-thaw model (CRREL model). Through modifications of, additions to, and deletions from these modules, the FHWA integrated model was developed to combine these modules into one major pavement structure and subgrade analysis.

The Precip model, developed at TTI, provides the amount of rain and the day on which rainfall occurs. The Precip model is designed to be applicable wherever rainfall amounts and patterns are required for pavement engineering design. The model uses mathematical concepts to simulate rainfall patterns.

The ID model, also developed at TTI, performs several functions: the pavement base course drainage evaluation, the probabilistic analysis of the rainfall data, the infiltration analysis, and the resulting probabilities of having either a wet or dry base course.

The CMS model was developed at the University of Illinois (*2*). The model computes the temperature profile throughout an asphalt pavement and the heat flux boundary condition on the roadway surface from air temperature, wind speed, solar radiation, and sunshine percentage. Changes with time of asphalt stiffness, resilient modulus, and Poisson's ratio of the base, subbase, and subgrade are also determined by the CMS model. Inputs to this model include the material properties, pavement geometry, and several other parameters.

The CRREL model was developed at the U.S. Army Cold Regions Research and Engineering Library (*3*). This model can provide a measure of frost heave because it includes a phase change of water to ice. The CRREL model uses the temperature profile through the asphalt layers, which is determined by the CMS model, to calculate changes in the soil temperature profile and, accordingly, frost penetration and thaw settlement.

An analysis of the FHWA integrated model revealed that it provides several options for temperature prediction that are not included in other models. The integrated model predicts temperatures not only at the pavement surface, but also at nine other nodes located at depths anywhere within the asphalt surface, base courses, or subgrade. Figure 1 shows the variation in pavement temperatures with depth as predicted by the model for a typical pavement system subjected to averaged climatic conditions over a 3-day period.

EFFECTS OF ACTUAL CLIMATIC DATA

The integrated model has the option for the user to either input the climatic data or to use the default climatic data provided by the model. The model currently includes files consisting of typical weather information for 15 U.S. cities. It also includes files that contain averaged weather conditions for the six climatic regions within the United States. It is possible to obtain geographically realistic pavement temperature predictions from the integrated model even if no specific weather information is available to the user. Pavement temperature predictions made using the model's default climatic data will not be as accurate as predictions made using the actual weather conditions from a site. However, with this option, the integrated model provides the opportunity to subject one pavement system to various climates without gathering any weather data.

When the option of entering the weather information is chosen, the Precip model and the CMS model use mathematical methods to create the four input files that contain climatic data. Alternatively, the data in these files can be directly input, if accurate historical data are available. Figure 2 shows a comparison of the results between two runs for a typical pavement system in Washington, D.C. For the first run, the input file included actual minimum and maximum daily air temperatures for Washington, D.C., in 1987. For the second run, the model was run using the included default weather files for Washington, D.C. All other variables were held constant between the two runs.

When the included default air temperatures are used, a regular pattern of pavement temperatures is predicted. This pattern is to be expected because the default temperatures are typical minimum and maximum air temperatures averaged over a multiyear period. Accordingly, the extremes are averaged out, and no significant peaks or valleys occur in the pavement temperature predictions.

When the actual minimum and maximum air temperatures are used, the predicted pavement temperatures follow a more random pattern. On days when the air temperature rises or falls from the norm, the predicted pavement temperatures change correspondingly. Highs, lows, and rates of heating and cooling vary with the air temperatures. This more realistic pattern of predicted pavement temperatures illustrates how the inclusion of actual climatic data can improve the accuracy of the results.

COMPARISON WITH MEASURED PAVEMENT TEMPERATURES

Figure 3 shows two plots of predicted pavement temperatures for Washington, D.C., during 2 different weeks in February. These temperatures were predicted for a typical pavement system using the integrated model. The run used actual climatic data for Washington, D.C. The asterisks that appear

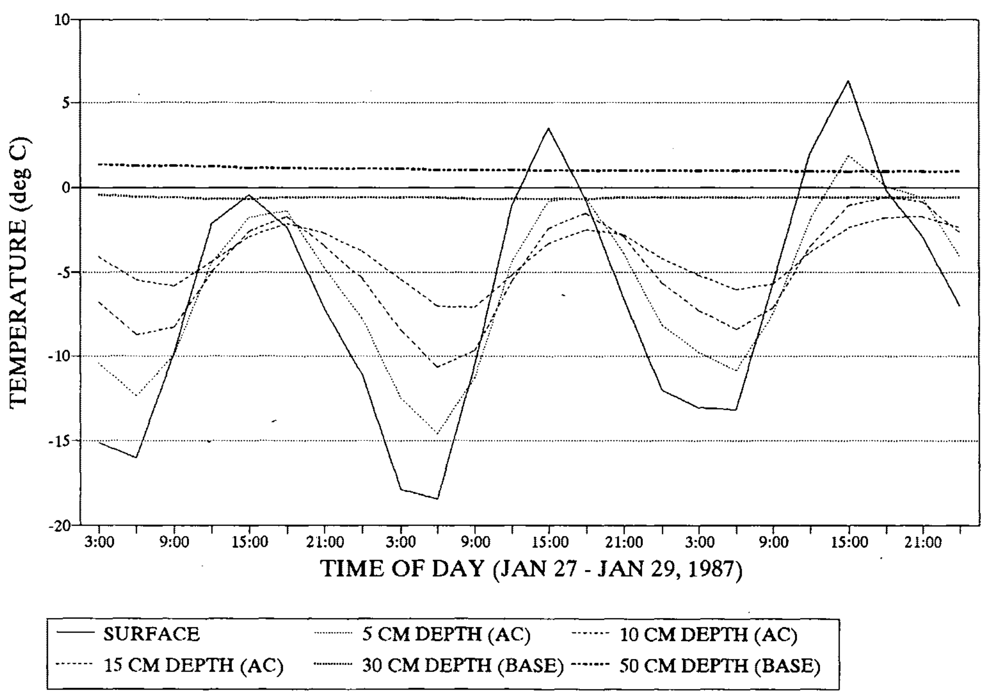

FIGURE 1 Variation of integrated models' predicted temperatures with depth in pavement.

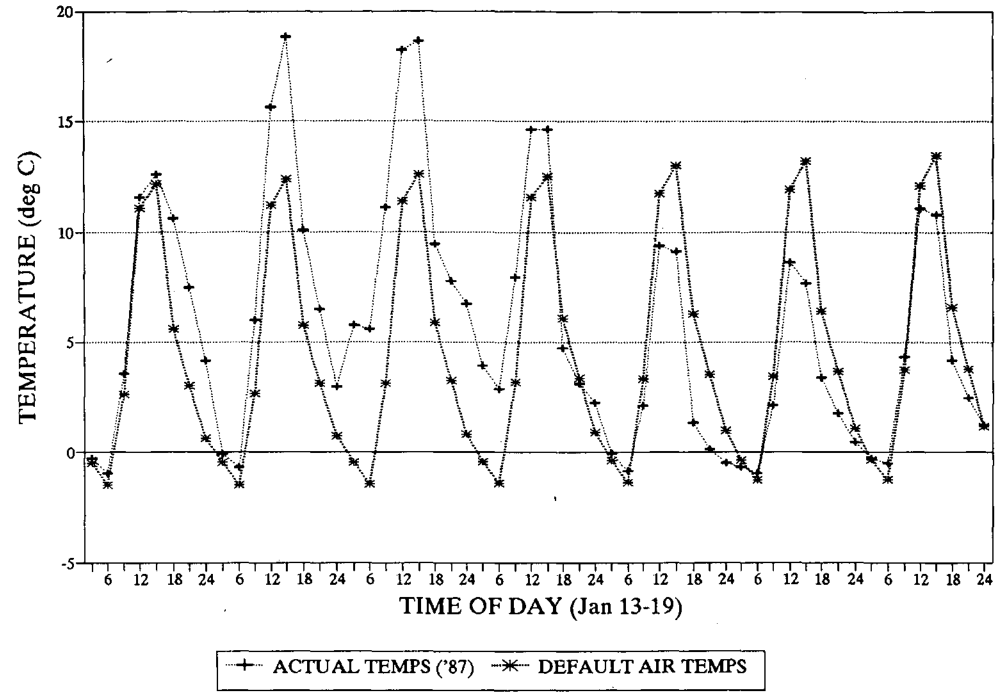

FIGURE 2 Effect on predicted pavement temperatures of using actual air temperatures in integrated model.

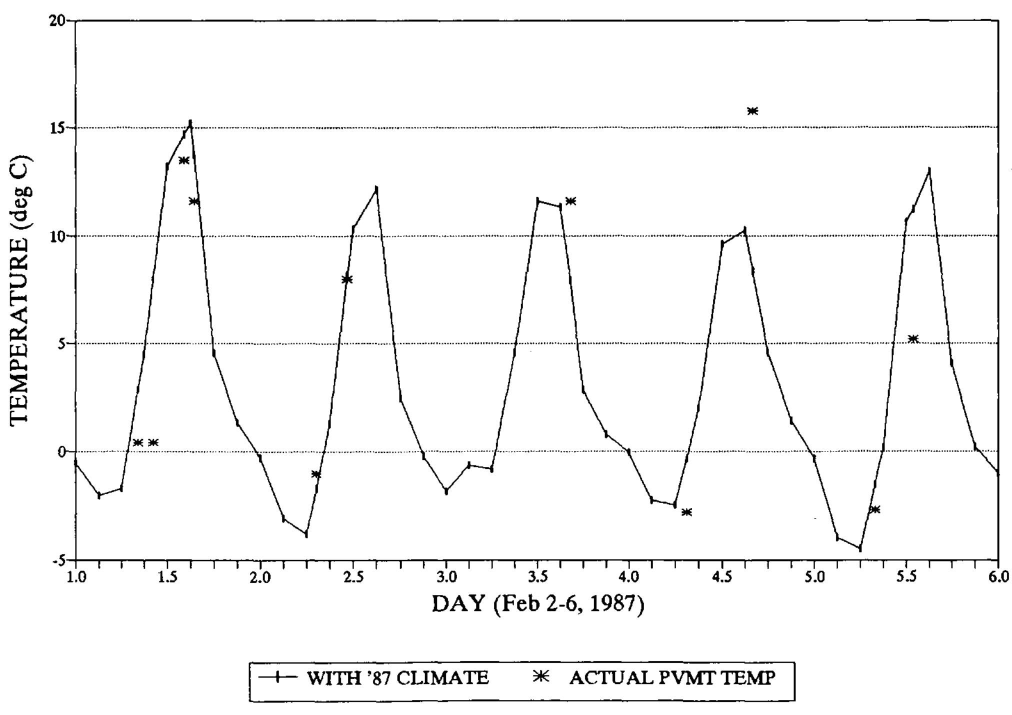

FIGURE 3 Comparison of predicted pavement temperatures with measured pavement temperatures.

sporadically throughout the plot mark actual recorded pavement temperatures from a pavement at the FHWA Accelerated Loading Facility near Washington, D.C. The integrated model's predictions consistently correspond with the measured pavement temperatures. Additional comparisons were made but cannot be illustrated here. With the entire climate appropriately represented, a near match usually occurs.

FHWA INTEGRATED MODEL COMPARED WITH OTHER MODELS

The FHWA integrated model was compared with two other computer programs that include environmental effects models: COLD and THERM. These two models were chosen for comparison because they are capable of predicting pavement temperatures and are used within the pavement design community.

Analysis with COLD

The computer program COLD consists of two separate computer programs, both developed at the University of Alberta by Christison and Anderson (*4*). Together, these two programs perform computations of low-temperature damage (COLD) in a given pavement system. One of the programs predicts temperatures in a layered pavement system, and the other predicts thermal stresses in the surface layer caused by the temperature changes. Of the two main components of the program COLD, only the first, the temperature prediction model, was evaluated. This component uses air temperatures and solar radiation data to calculate pavement temperatures.

COLD uses finite difference equations to calculate pavement temperatures. These equations assume a one-dimensional heat transfer program. The inputs needed by the program are air temperatures, solar radiation values, and the thermal properties of component layer materials. The program provides an option for entering the daily temperatures and solar radiation data; either temperature and solar radiation data can be entered for every hour of the day, or the maximum and minimum temperatures for each day and the daily solar radiation values can be entered.

The integrated model was compared with COLD. Figure 4 shows the pavement temperatures predicted by COLD both when the daily air temperatures are entered and when the hourly air temperatures are entered. Figure 4 includes the FHWA integrated model's predictions and the air temperatures over the same period.

The pavement temperatures predicted by COLD for this example are unrealistic. The rates of heating and cooling, especially when daily air temperatures are entered, are extremely exaggerated. COLD repeatedly predicts pavement temperatures ranging from 25°C to 50°C (50°F to 90°F) higher than the day's highest air temperature.

Analysis with THERM

The computer program THERM was developed at TTI, Texas A&M University (*5*). The program is intended to provide a design procedure for asphalt pavements to resist thermal fatigue cracking. THERM uses fracture mechanics to predict transverse cracking caused by thermal fatigue cracking in asphalt concrete pavements.

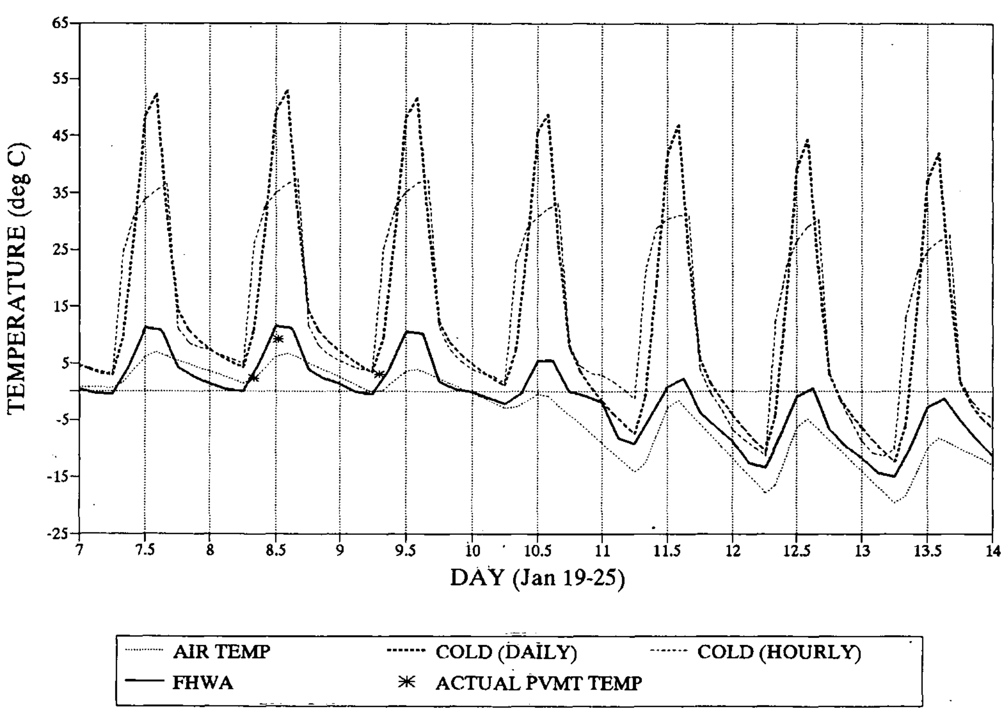

FIGURE 4 Comparison of predicted pavement temperatures between integrated model and COLD.

The first step in this procedure is the prediction of pavement temperatures. THERM computes these temperatures by using Shahin's and McCullough's revision of Barber's equation (*6,7*). Barber's equation is an empirical heat flow model that uses ambient temperatures, solar radiation, and wind velocity to predict pavement temperatures.

The integrated model was compared with this pavement temperature predicting portion of THERM. Figure 5 shows a comparison between the predicted pavement temperatures from each of these models for a typical pavement section in Fargo, North Dakota, using typical data. The pavement temperatures predicted by THERM remain relatively stable throughout the day with an extreme increase immediately before noon and an extreme drop-off immediately after noon.

Results

The FHWA integrated model predicts pavement temperatures much more realistically than either the COLD program or the THERM program. Both of these models tend to predict unreasonably high pavement temperatures at some point in the afternoon. It is only with the high temperatures, however, that these models vary so much from reality; the lowest temperatures predicted by these two models follow closely with the FHWA integrated model's predictions. Accordingly, both COLD and THERM might predict low temperatures accurately enough to design for basic low-temperature cracking. However, because of the extremely high pavement temperatures predicted during each afternoon, an exaggerated amount of cooling per hour is implied each evening.

CONSIDERATION OF PAVEMENT EDGE EFFECTS

The computer program TDHC (two-dimensional heat conduction) was developed in Fairbanks, Alaska, by Goering and Zarling (*8*). TDHC uses finite element modeling techniques to solve two-dimensional nonsteady-state heat conduction problems. These problems may include phase change, thermal properties that vary within the region and with the state of the material, and several types of boundary conditions.

The TDHC program was used to determine the effect of edges, if any, on pavement temperatures. Most of the environmental effects models available, including the FHWA integrated model, assume an infinite slab and predict temperatures that represent the temperature at the center of the pavement. One question with this approach is whether the temperature at the center of the pavement varies with the cross section of the pavement. For example, the temperature at the center of a level pavement with asphalt concrete shoulders may not be the same as that of a pavement with exposed sides and gravel shoulders. In such a case, pavement temperatures predicted for an infinite slab would be inaccurate and inappropriate for design.

Another potential problem with the infinite slab assumption is that the predicted temperatures represent the pavement temperature at the center of the slab. However, a pavement is not designed for the centerline only; the temperature profile across the cross section is also important. If much variation exists between the temperature at the center of the slab and the temperature elsewhere in the pavement, the centerline temperature may not be the appropriate temperature to use during design.

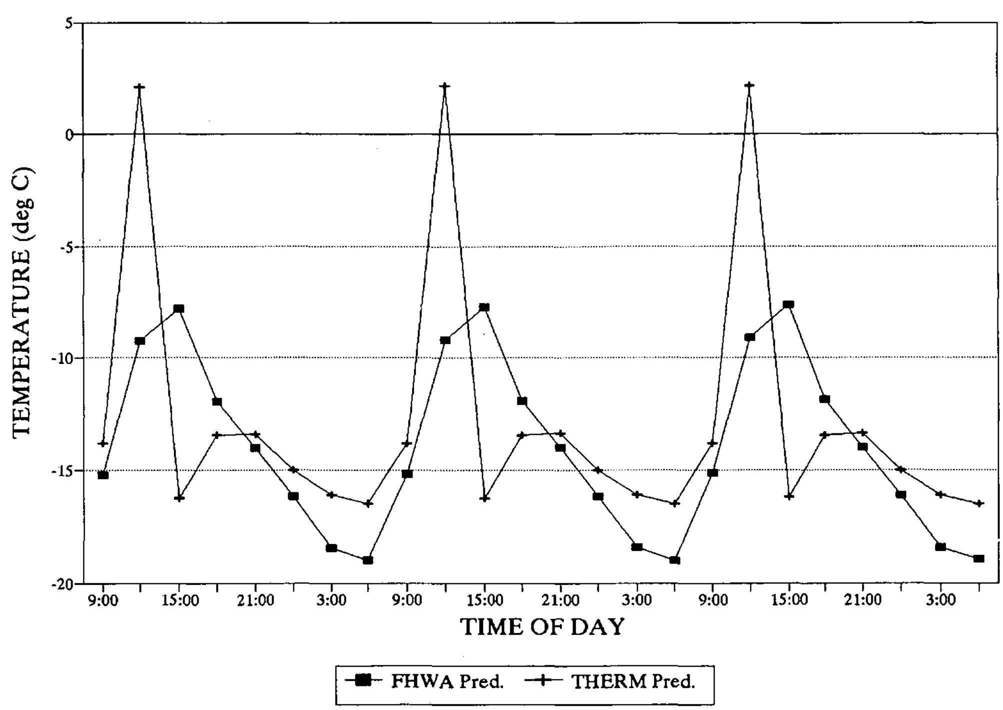

FIGURE 5 Comparison of predicted pavement temperatures between integrated model and THERM.

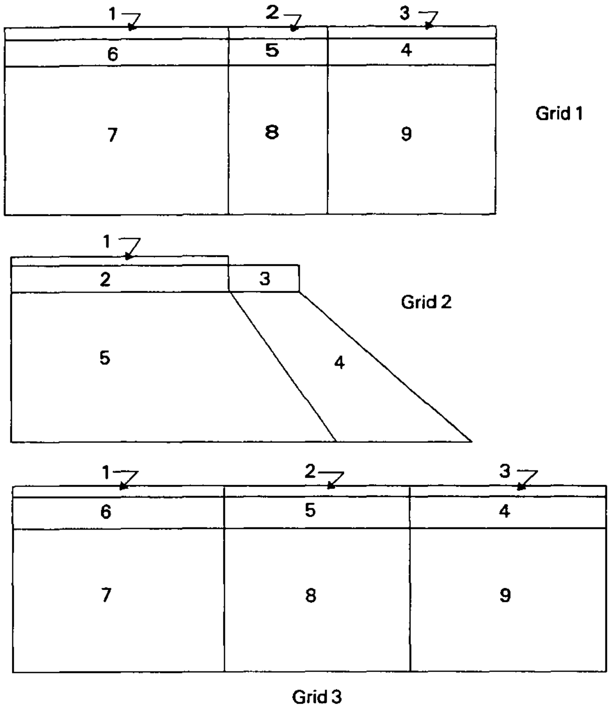

FIGURE 6 Grids used in TDHC evaluation.

Analysis with TDHC

Three grids were chosen to represent varying boundary conditions and are represented schematically in Figure 6. These grids were created using the program GRIDGEN, a preprocessor designed to prepare a portion of the data file required for TDHC. To use GRIDGEN, the user must first divide the region into subregions, each initially having homogeneous material properties. GRIDGEN automatically locates the nodes within the region and then subdivides the regions into linear triangular elements. After triangularization, the nodes are renumbered to achieve a minimum bandwidth. Because each grid is symmetric, it is possible to model only one-half of the entire pavement system. The final Grid 1 is shown in Figure 7.

Grid 1 represents a realistic pavement. The pavement has two asphalt concrete (AC) lanes 365 cm (12 ft) wide, 15 cm (6 in.) deep, each with a 180-cm (6-ft) AC shoulder. Beyond the shoulders extends 300 cm (10 ft) of gravel base. This entire top layer measuring 1700 cm (56 ft) wide is exposed to varying boundary (temperature) conditions. Below this top layer is a gravel base layer 30 cm (12 in.) deep. Below the base is 490 cm (16 ft) of silty subgrade.

Grid 2 represents an extreme situation. The pavement once again has two AC lanes 365 cm (12 ft) wide, 15 cm (6 in.) deep. However, no shoulders are included in this case. Below each lane is gravel base 30 cm (12 in.) deep. Extending beyond this base is 120 cm (4 ft) of silty subgrade. As with the first case, below the base is 490 cm (16 ft) of silty subgrade. This subgrade, however, starts at the edge of the base and slopes downward at a 45-degree angle for the 490 cm (16 ft). The surface and the sloping sides of this pavement system are exposed to varying boundary conditions.

Grid 3 represents the infinite slab that is assumed in other environmental effects models. The pavement has AC that is 2200 cm (72 ft) across and 15 cm (6 in.) deep. Below this entire layer is gravel base 30 cm (12 in.) deep. Below the base is 490 cm (16 ft) of silty subgrade. Only the AC surface is exposed to the boundary conditions.

Table 1 gives the type of material making up each subregion and the initial temperature of each subregion for each of the

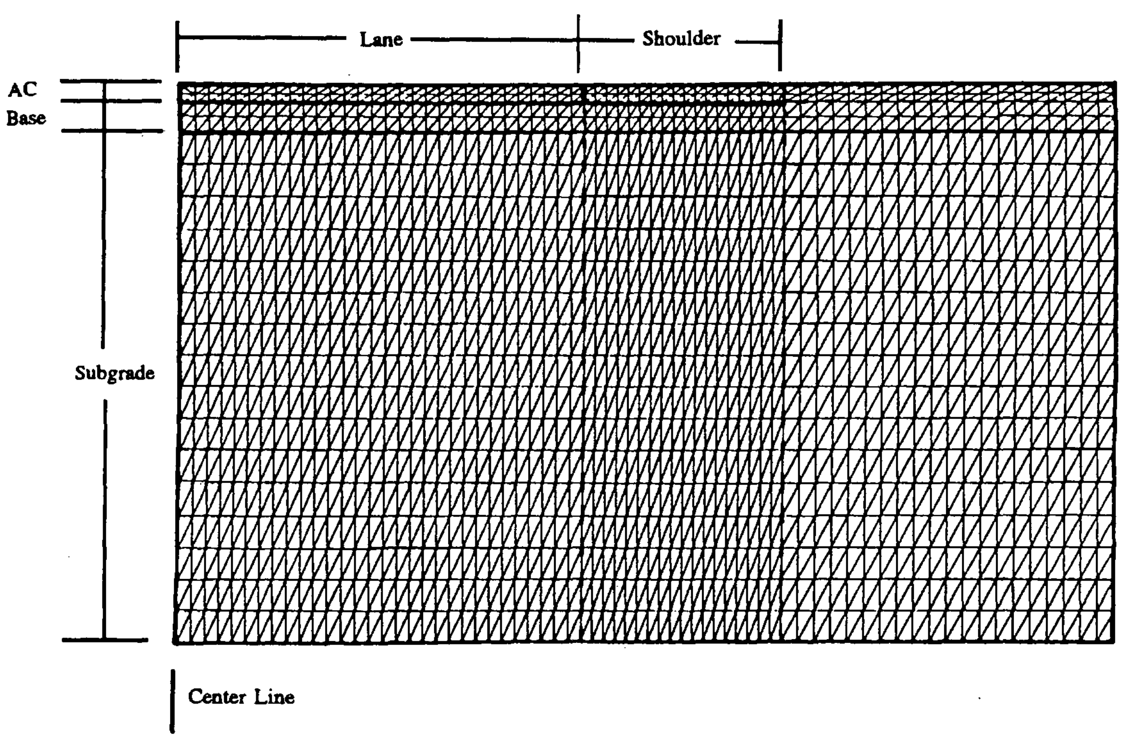

FIGURE 7 Grid 1 of TDHC runs: a "realistic" pavement.

TABLE 1 TDHC Inputs: Division of Grids

Grid	Subregion	Material	Initial Temperature °C (°F) DC	FARGO
1	1	AC	-1.1 (30)	-16.7 (2)
	2	AC	-1.1 (30)	-16.7 (2)
	3	Gravel	-1.1 (30)	-16.7 (2)
	4	Gravel	1.1 (34)	-8.3 (17)
	5	Gravel	1.1 (34)	-8.3 (17)
	6	Gravel	1.1 (34)	-8.3 (17)
	7	Silt	7.8 (46)	1.7 (35)
	8	Silt	7.8 (46)	1.7 (35)
	9	Silt	7.8 (46)	1.7 (35)
2	1	AC	-1.1 (30)	-16.7 (2)
	2	Gravel	1.1 (34)	-8.3 (17)
	3	Silt	-1.1 (30)	-16.7 (2)
	4	Silt	7.8 (46)	1.7 (35)
	5	Silt	1.1 (34)	-8.3 (17)
3	1	AC	-1.1 (30)	-16.7 (2)
	2	AC	-1.1 (30)	-16.7 (2)
	3	AC	-1.1 (30)	-16.7 (2)
	4	Gravel	1.1 (34)	-8.3 (17)
	5	Gravel	1.1 (34)	-8.3 (17)
	6	Gravel	1.1 (34)	-8.3 (17)
	7	Silt	7.8 (46)	1.7 (35)
	8	Silt	7.8 (46)	1.7 (35)
	9	Silt	7.8 (46)	1.7 (35)

three grids. The number of each subregion corresponds to the subregion numbers in Figure 6. Table 2 includes the material properties (thermal conductivity, volumetric specific heat, volumetric latent heat) of AC, gravel, and silt as they were used for this analysis.

The "exposed" surfaces of each of the three grids were considered to be boundaries with harmonically time-varying temperatures. Boundaries with such harmonic temperatures are treated by setting each node along the boundary to the temperatures specified. Harmonic time-dependent temperatures are based on the following equation:

$$T = T_m - A_m \cos(2\pi t/365 - 2\pi\phi/365)$$

where

- T = time-dependent temperature,
- T_m = mean temperature,
- A_m = temperature amplitude,
- t = time, and
- ϕ = phase factor.

This equation can be used to fairly accurately represent the yearly ambient air temperature if T_m is set to the mean annual air temperature, A_m is set to the annual air temperature amplitude, t is in days from January 1, and ϕ is the phase lag of the temperature cycle in days from January 1. These values for Washington, D.C., and Fargo, North Dakota, were obtained from data provided by the National Oceanic and Atmospheric Administration.

First Set of Runs

For the first set of runs (a set consisting of six runs, each of the three grids being run for each of the two cities), the run time was set for 0.2 year, or 75 days. The model started from January 1 and used a time step of 1 day. With this time step, the temperature values at each node were updated and recorded once each day. These temperature values are not representative of any specific time of day. This is because the equation used to calculate the ambient temperature provides only one temperature per day, not a temperature curve that varies with the time of day.

Second Set of Runs

The second set of runs produced daily cooling rates from hourly temperatures for each case. This was accomplished by manipulating the inputs to the model, which are based on 1-year runs, to represent 1 day. For example, the maximum and minimum temperatures for 1 day in January in Fargo, instead of 1 year, were used to determine the mean temperature and amplitude values used by the program to calculate the varying temperatures. This was possible because daily temperatures, as with yearly temperatures, are cyclical. Also, the values for thermal conductivity (cal/cm · sec · °C) or (Btu/ft · hr · °F) had to be scaled down to represent the total amount of heat that could be transferred in 1 day, not in 1 year.

For this set of runs, the run time was set for 31.2 "hours," or 1.3 years, and the time step was every "hour," or every 15.2 days. The model started at "noon," 12 "hours" into the day, or at Day 183. The results from these runs, then, were the hourly temperatures from noon until 7:00 a.m.

TABLE 2 TDHC Inputs: Material Properties

	Thermal Conductivity Cal/cm.sec°C (BTU/ft-hr-degF)		Volumetric Specific Heat Cal/cm³ - °C (BTU/cu.ft.-degF)		Volumetric Latent Heat Cal/cm³ (BTIci/ft)
	frozen	thawed	frozen	thawed	
AC	194 (0.80)	194 (0.80)	.42 (26.4)	.42 (26.4)	.89 (100)
Gravel	339 (1.40)	363 (1.50)	.43 (27.0)	.48 (29.7)	6.67 (750)
Silt	184 (0.76)	179 (0.74)	.41 (25.3)	.49 (30.8)	13.35 (1500)

Results from TDHC

The output file from a TDHC run includes the temperature of each node of the grid for each time step. If large grids, such as those used in this analysis (Grid 3 had 1,547 nodes), are run for extended time periods (75 days for the first set of runs), the output files may be very large. This analysis produced some output files that filled over 3 MB of space.

Three different approaches were taken to analyze the results of the TDHC program. First, the temperature profile across the pavement was considered to determine the difference in temperature between the edge of the pavement and the center of the pavement. Figure 8 shows the temperatures at a 6-in. depth along the cross section of the pavement. These results represent February 22 in Fargo, North Dakota.

For each grid, the predicted temperatures across the pavement follow a logical pattern. Grid 3, the infinite slab, shows little variation in temperature because there are no edge effects. Grid 1, the realistic pavement, shows little variation in temperature until the shoulder, which is insulated on one side only by a gravel base material. This temperature drop, however, is less than 0.5°C (1°F) and occurs solely in the shoulder. Grid 2, the extreme case, shows that the temperature decreases from the center of the slab to the edge of the slab, with the most significant drop occurring in the 4 ft closest to the edge. Even with Grid 2 much less insulated from temperature changes, the difference between the temperature at the center of the pavement and at the edge of the pavement is no more than 1°C (2°F).

Next, the centerline temperatures for each grid were considered to determine how the different boundary conditions affect the temperatures at the center of the slabs. These center temperatures were found to not vary with the boundary conditions imposed.

Finally, the daily cooling rates at the center of the pavement and at the edge of the pavement were compared to ascertain whether any large discrepancies existed. Grids 1 and 2 were used for this comparison because differences between center and edge temperatures occur with these grids.

Figure 9 shows the cooling curves for Grid 1. The center of the pavement and the edge of the pavement cool at almost the same rate. The edge of the shoulder, which is insulated by a gravel layer, cools at a slightly faster rate and varies from being at almost the same temperature as the center to being around 2 degrees cooler than the center. Between the hours of 11:00 p.m. and 8:00 a.m., the center of the pavement cools at approximately 0.58°C/hr (1.04°F/hr). The edge of the pavement, however, cools at approximately 1.19°C/hr (1.27°F/hr), about 25 percent faster than the center.

Figure 10 shows the cooling curves for Grid 2. The edge of the pavement, which is highly exposed to the varying air temperatures, cools at a faster rate and varies from being at almost the same temperature as the center to being more than 10 degrees cooler than the center. Between the hours of 11:00 p.m. and 8:00 a.m., the center of the pavement cools at approximately 0.58°C/hr (1.04°F/hr). The edge of the pavement, however, cools at approximately 1.19°C/hr (2.14°F/hr), more than twice as fast as the center.

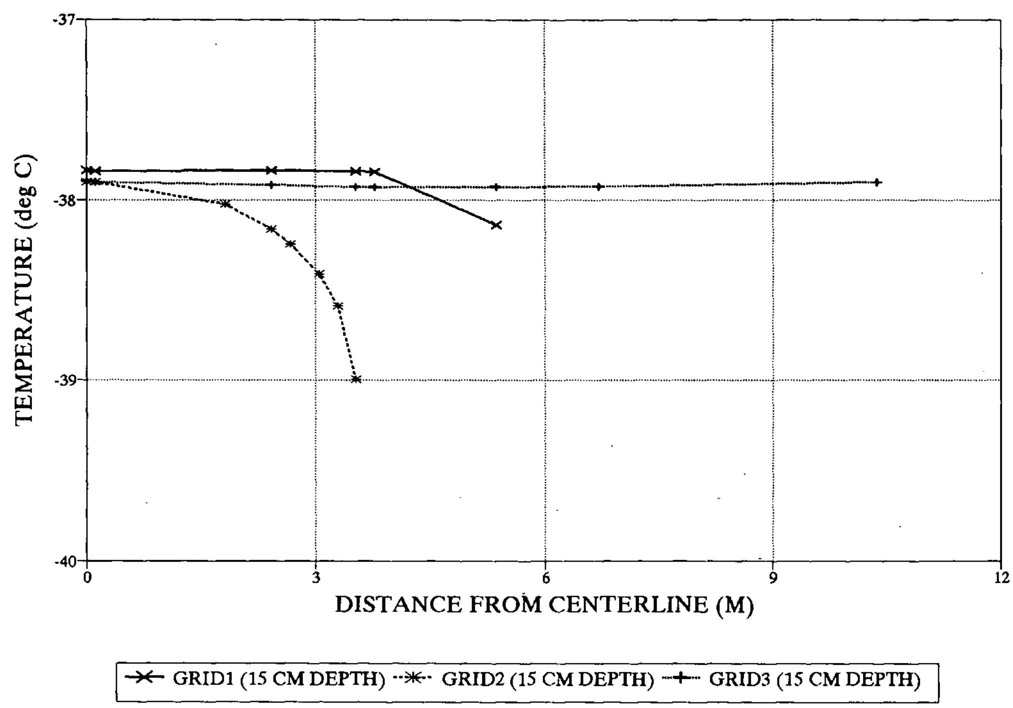

FIGURE 8 Cross-sectional profile of TDHC predicted temperatures for each grid.

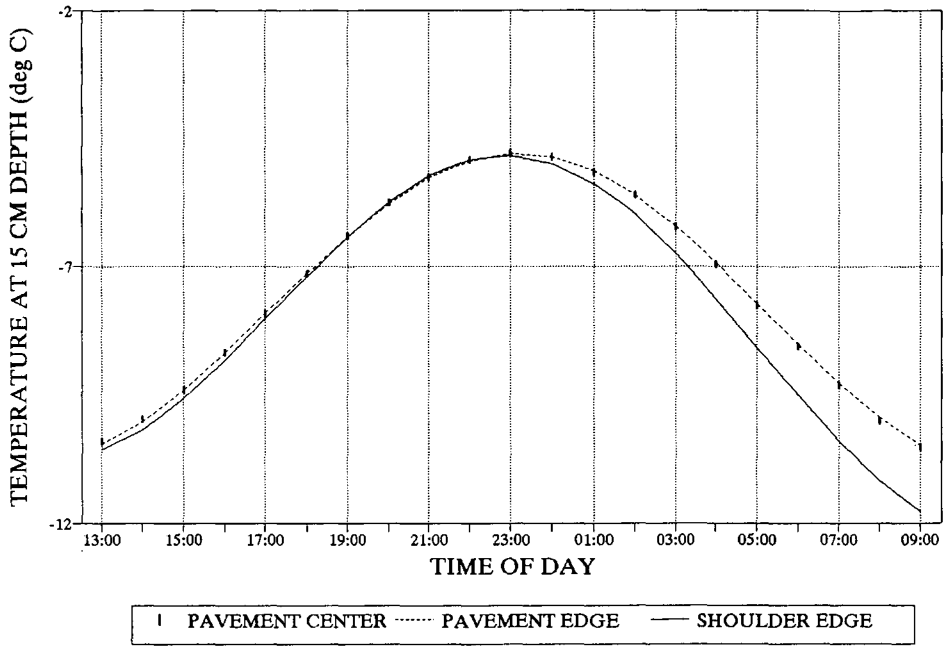

FIGURE 9 Daily cooling curve for Grid 1.

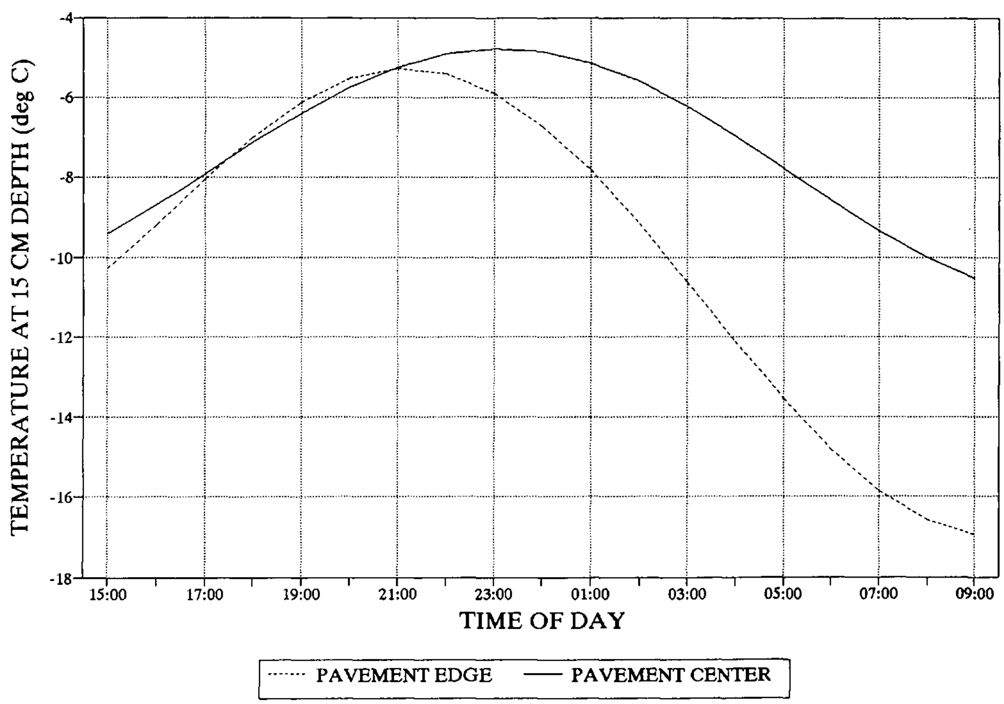

FIGURE 10 Daily cooling curve for Grid 2.

CONCLUSIONS

The FHWA integrated model predicted pavement temperatures that corresponded to available recorded pavement temperatures. The model also predicted pavement temperatures that followed ambient temperatures in a logical manner, unlike other environmental effects models such as COLD or THERM.

The FHWA integrated model is a very comprehensive environmental effects model. No other available models simulate the actual climate as effectively as the FHWA integrated model. This model accounts for air temperatures, solar radiation, amount and type of precipitation, sunshine percentage, and windspeed. The model's accuracy is enhanced because it deals with all of these factors hourly. Many models consider only one time a day, smoothing out relevant extremes.

The FHWA integrated model is a user-friendly model that could easily be adopted into state department of transportation programs. Although the model requires an unusually large number of inputs, it provides reasonable default values for most of these that can be used wherever specific data are missing. Also, the program can predict pavement temperatures three times a day for the entire winter season (4 months) in approximately 5 hr. This is a reasonable run time considering the many outputs produced by the model.

The pavement temperatures predicted by the FHWA integrated model represent the temperature at the center of the pavement. The model assumes the pavement system to be an infinite slab with no edges transferring heat only in the vertical direction. The evaluation of the TDHC model, which accounts for edges and is capable of two-dimensional heat flow, justified this assumption for most situations.

The results from the TDHC model showed that the cross section of the pavement system does not significantly affect the temperature at the center of the pavement. However, shoulders and exposed pavement edges may cool significantly faster than the pavement centerline. The FHWA integrated model can be used to predict asphalt concrete pavement temperatures in most situations. If a pavement system is abnormally exposed to its environment, a more detailed look at its temperatures, such as that provided by the TDHC model, may be needed.

The TDHC model, considering the shape of the pavement system and permitting two-dimensional heat flow, takes a long time to run. A 1,550-node grid can be run for 75 days, producing only one temperature per day in approximately 6 hr. An 800-node grid can be run for 35 days in approximately 2 hr.

The TDHC model is most useful for extreme situations. If a pavement system is suspected to be unusually exposed to the environment, the TDHC model can provide the pavement temperature profile across the pavement and the cooling rates across the pavement. Such information cannot be obtained from the FHWA integrated model.

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