Rational Weather Model for Highway Structures

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Empirical time-dependent equations for ambient air temperature, solar radiation, and wind speed are presented for summer and winter air temperature extremes at two sites for hourly solar radiation-surface meteorological observations (SOLMET): Columbia, Missouri, and Fairbanks, Alaska. The time-dependent equations, in recurrence periods from 1 to 100 years, give engineers a rational basis for selecting a climatic exposure for a desired design period. These time-dependent models may be incorporated into finite element or finite difference heat-flow programs to calculate temperature variations through members of highway structures. Examples demonstrate how a weather exposure may be selected at a geographic location. Mean recurrence of bridge temperature is presented for composite, box girder and T-beam bridges. The Fairbanks, Alaska, models of weather exposure were used previously to study thermal stresses and movements for a 50-year design event in a jointless composite-girder bridge located in the Arctic.

Ambient air temperature, solar radiation, cloud cover, wind, and precipitation are predominant atmospheric components of weather that cause heat flow in highway structures (*1–6*). These atmospheric phenomena cause temperatures in outdoor structures to vary nonlinearly with time; temperature changes induce thermal movements and stresses. The magnitude of thermal movements and thermal stresses are affected by temperature profiles, superstructure geometry, material properties, and restraints imposed by connections and substructure stiffness.

The design of structures that are safe and maintenance-free may require two types of weather models to account for thermal effects: one to account for weather extremes with a return period and the other to characterize daily chaos over time so that material damage accumulation may be examined. The importance of these complex time-dependent weather-structure interaction phenomena in relation to other loads is not well understood (*7–10*).

Because of the complex nature of an environmental exposure, there has been some reluctance to determine recurrence for thermal loading. In 1984, Church and Clark (*7*) presented probable combinations of highway and temperature difference loads. Recurrences in temperature differences were based on a guess of observed bridge gradients by Emerson (*11*) for the British Isles and later modified. Potgieter and Gamble (*4*) studied prestressed bridges for extremes at 26 climatic sites established by the National Oceanic and Atmospheric Administration for hourly solar radiation-surface meteorological observations (SOLMET). Later Kuppa and Roeder (*6*) used 11 climatic SOLMET data sites to study extremes in thermal movements for three bridge types. Neither study compared exposures to a return period. Hulsey (*2*) and later Hulsey and Powell (*5*) showed that recurrence periods may be determined for annual temperature extremes. In 1989, Ho (*10*) suggested a random technique for 50-year extremes of thermal highway loading on highway bridges in which attention was given to a statistical approach.

A weather model is presented in this paper to provide a mechanism for assessing environmental factors on response and performance of highway structures. The model approximates maximum summer or minimum winter air temperature days with return periods of 1 to 100 years at two sites: a cold climate in Fairbanks, Alaska, and a hot climate near Columbia, Missouri. Daily maximums, averages, and minimums also are presented for air temperature and solar radiation at each site. This type of model may be used to compare structural temperature profiles from different climates. No attempt is made to include precipitation, wind fluctuations, or spring and fall conditions or to characterize diurnal irregularities. These considerations are under study and will be presented later.

BACKGROUND

Bridge engineers use two design approaches to account for thermal effects: expansion devices and jointless decks. The conventional design approach assumes that bridge deck expansion devices and expansion bearings allow bridges to expand or contract without restraint. Yet it is common to find improperly tilted and frozen bearings, inoperative expansion devices, and distressed appurtenances; these examples show that free movement does not exist (*12*). Some states design bridges with jointless decks supported by bearings or flexible bents, or both (*6,12–14*). In either case, Emanuel and Taylor (*15*) showed that bridge length does not influence stress inducement.

The methodology for calculating movements and stresses involves three steps: (a) characterizing climatic exposure; (b) determining structural temperatures with respect to construction conditions; and (c) using the internal strains caused by temperature to calculate deformations and strains and stresses (*2,4,9,14,16–19*).

Most research to date has focused on Step b, identifying temperature profiles for different bridges of various exposures, or Steps b and c, assessing stresses and movements for different bridge types. Bridge temperatures in the literature

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are usually based on field-measured structure temperatures (*16,17,20–22*), calculations using exposures measured for a limited time (*19*), or laboratory studies (*15,18,23–25*). Some studies have used climatic data to approximate extremes (*2–6,14*). Others have approximated temperature profiles with polynomials (*8,9,21,26*), but no provisions were made for differences in climate or return periods.

In summary, weather-induced thermal stresses can be large and should be considered in design, little understanding exists of the interaction between weather and induced movements and stresses, and AASHTO gives limited guidelines to account for movements, with no guidelines for thermal stresses and no provision for regional climates and design periods. Prediction of induced thermal stresses and movements necessitates a rational method for determining both extreme weather conditions affecting structures in a given geographic region and anticipating climatic conditions over the life of the facility.

SITE CLIMATIC DATA

Tapes were examined of hourly surface observations for Fairbanks, Alaska (1952–1976) and Columbia, Missouri (1946–1965), combined with annual summaries to 1987 (*27*). Fairbanks is at a latitude of N64°49′ and Columbia is N38°45′.

Irregularities aside, weather follows two trends: annual and diurnal. Annual trends account for seasonal change from winter to summer and diurnal trends account for warming during the day and cooling at night. Daily trends may be altered by clouds, precipitation, and circulating cool or warm air masses to the region (*2,3*).

Annual Trends and Extreme Events

Heat transfer occurs through a highway structure by conduction, convection, solar radiation, and thermal long-wave radiation. Climatic boundary conditions such as air temperatures influence both long-wave radiation and convection, wind contributes to convective cooling, and solar flux provides heat to pavements and bridge decks (Figure 1). Precipitation can modify these influences. If contributions of precipitation and variations in wind velocity are ignored, daily accumulated heat transfer energy on the boundaries is a function of ambient air temperature (T_d), solar radiation (Q_d), wind (v), for day (d), or

$$q(t) = f[T_d(t); Q_d(t); v; \ldots] \qquad t = d \text{ (annual)} \tag{1}$$

Empirical annual expressions for each of the contributions of Equation 1 were determined for Fairbanks, Alaska, and Columbia, Missouri, and are presented herein for consideration.

Ambient Air Temperature

It is valid to assume that annual trends in ambient air temperature will follow a periodic cycle (*2*) of the form

$$T_d = A_d \sin\left[\frac{2\pi(d - \gamma)}{365}\right] + B_d \qquad 0 \le d \le 365 \tag{2}$$

where

T_d = daily temperature,
A_d = annual temperature fluctuation about yearly average,

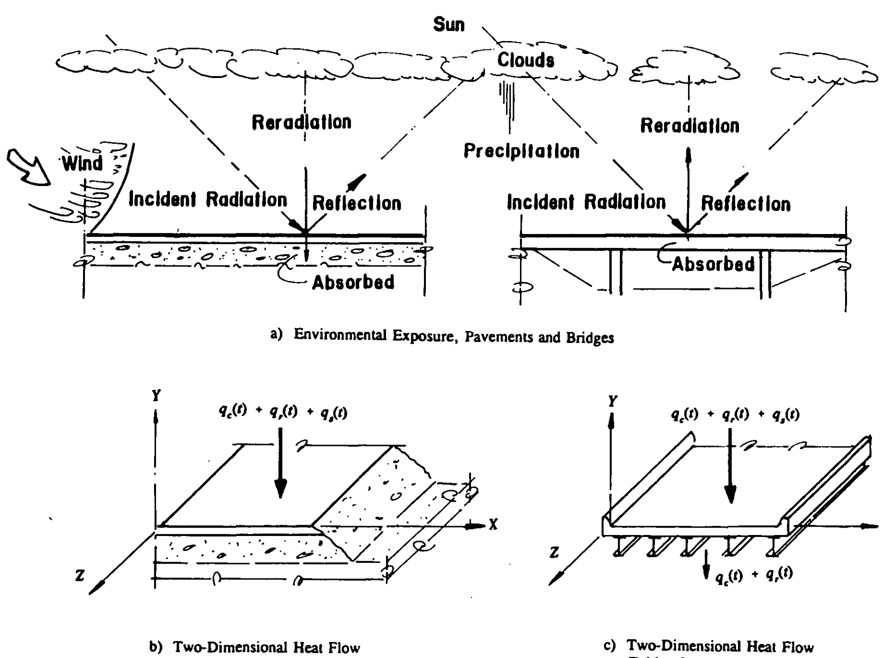

FIGURE 1 Pavements and bridges subjected to climatic conditions.

B_d = average yearly temperature,
γ = lag in days, and
d = day of the year.

Figure 2 presents record maximum, minimum, and average daily ambient air temperatures for the 25-year period 1952–1976 at Fairbanks, Alaska, and Figure 3 represents the 20-year period 1946–1965 at Columbia, Missouri. Applying the Equation 2 curve fit using a regression analysis (*28*) for record maximum, minimum, and average daily ambient temperatures resulted in curves A, C, and B, respectively. Curves D and E are high and low temperatures valid for concrete placement. Table 1 provides Equation 2 coefficients for $T_{\min}$, T_{avg}, and $T_{\max}$ without regard for recurrence.

Although both ambient air temperature and solar radiation influence bridge temperature profiles significantly, air temperature has a dominant effect (*2,16,17*). For present purposes, the weather model corresponds to ambient air temperature extremes.

Hourly tape temperature data and annual summaries identify yearly record minimum and maximum temperatures for the period 1930 to 1987 for Fairbanks, Alaska, and the period 1921 to 1987 for Columbia, Missouri. These annual maximum and minimum temperatures were separated into data sets and ranked in ascending order for each site. An estimate of recurrence is given elsewhere (*29*) as

$$t_p = \frac{N + 1}{m} \tag{3}$$

where

t_p = recurrence in years,
m = rank, and
N = number of years in data set.

The probability P that an annual temperature will be equaled or exceeded in a given year is

$$t_p = \frac{1}{P} \tag{4}$$

In 1941, Gumbel (*29*) reported that recurrence may be estimated statistically if probability is expressed in the form

$$P = 1 - e^{-e^{-b}} \tag{5}$$

where P is the probability of occurrence that an event will be equal to or greater than an extreme event, and e is the base of Napierian logarithms. For this study, b is given by

$$b = \frac{1}{0.7797\sigma}(T - \overline{T} + 0.45\sigma) \tag{6}$$

in which T is a temperature extreme with a probability P, $\overline{T}$ is the arithmetic average of annual temperature extremes in the data set, and σ is the standard deviation computed from

$$\sigma = \left[\frac{\Sigma\,(T - \overline{T})^2}{N - 1}\right]^{1/2} \tag{7}$$

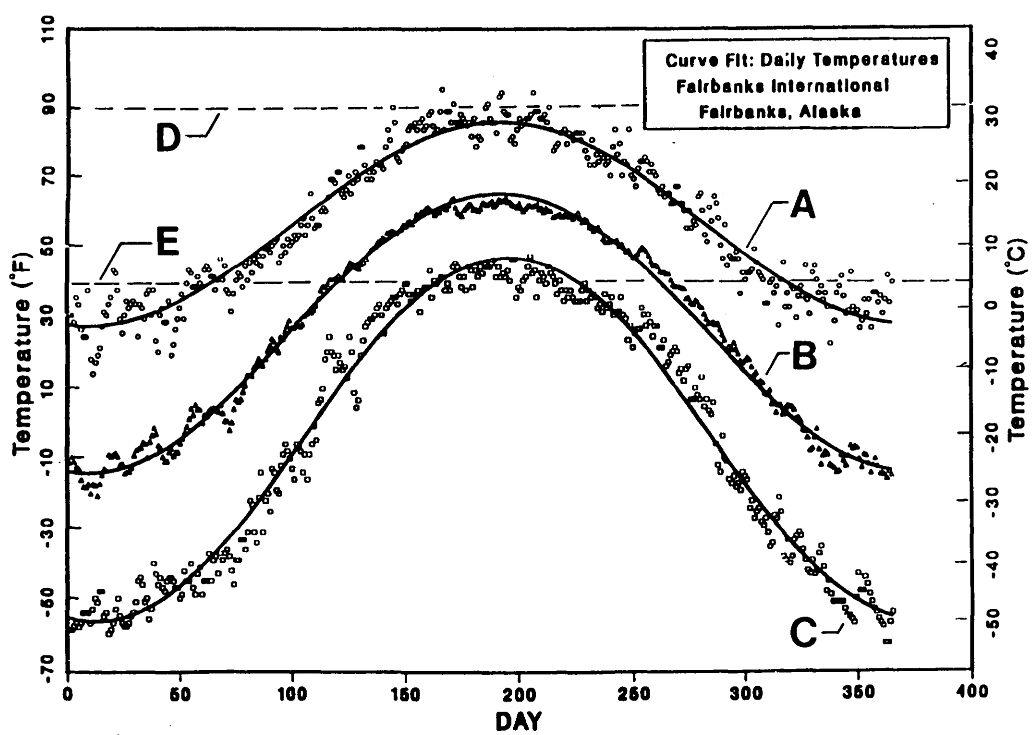

FIGURE 2 Curve fits for observed daily air temperature for the 25-year period 1952–1976, Fairbanks.

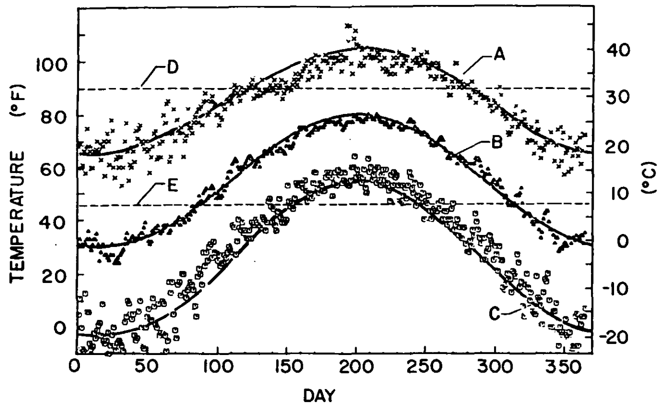

FIGURE 3 Curve fits for observed daily air temperature for the 20-year period 1946–1965, Columbia.

Return periods for yearly maximums and minimums of air temperature are shown in Figures 4 and 5, respectively, for the two sites. Assuming that the annual variation (A_d) and day lag (γ) of Table 1 are valid for maximum and minimum temperature return periods, B_d will vary with recurrence (Table 2). A ratio (ξ_y) is used to measure air temperature at some return period to the 100-year event. Each summer, maximum air temperatures are expected to reach ~82 percent of the 100-year event in Fairbanks and about 79 percent of a 100-year event in Columbia. The 100-year event in Fairbanks is 36.67°C (98°F) and in Columbia, 45.56°C (114°F). Each winter, minimum air temperatures are 43.8 percent of the 100-year event in Fairbanks and −36.3 percent in Columbia. The 100-year event in Fairbanks is −58.3°C (−73°F) and in Columbia, −32.78°C (−27°F).

Record temperatures between 1952 and 1976 for Fairbanks were 34.4°C (94°F), a 30-year event, and −52.2°C (−62°F),

TABLE 1 Ambient Air Temperature, Annual Trends

Site:	A_d		B_d		γ	High Temperatures, T_{max}				Low Temperatures, T_{min}			
Annual Temperatures	°F	°C	°F	°C	(days)	°F	°C	days	recur(yrs)	°F	°C	days	recur(yrs)
Fairbanks, Alaska:													
Maximum, $T_{d\,(max)}$	29	16.1	56	13.3	100	85	29.4	191-192	1.5	27	-2.8	8-9	--
Average, $T_{d\,(avg)}$	39	21.7	26	-3.3	100	65	18.3	191-192	--	-13	-25.0	8-9	--
Minimum, $T_{d\,(min)}$	51	28.3	-4.5	-20.3	104	46.5	8.0	195-196	--	-55.5	-48.6	12-13	5
Columbia, Missouri:													
Maximum, $T_{d\,(max)}$	20	11.1	85	29.4	110	105	40.6	201-202	10	65	18.3	18-19	--
Average, $T_{d\,(avg)}$	25	13.9	55	12.8	110	80	26.7	201-202	--	30	-1.1	18-19	--
Minimum, $T_{d\,(min)}$	30	16.7	25	-3.9	110	55	12.8	201-202	--	-5	-20.6	18-19	2

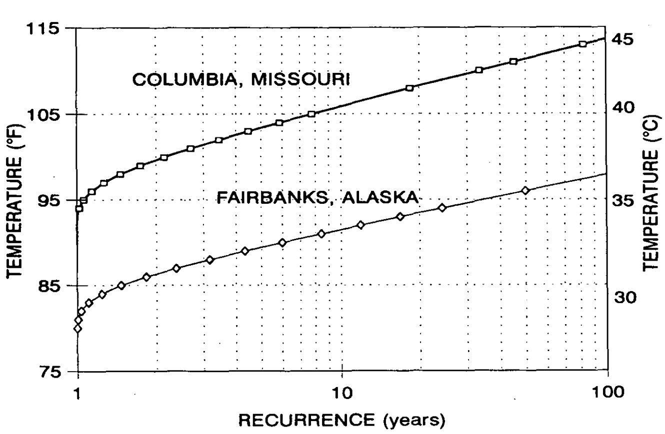

FIGURE 4 Recurrence for maximum daily air temperatures.

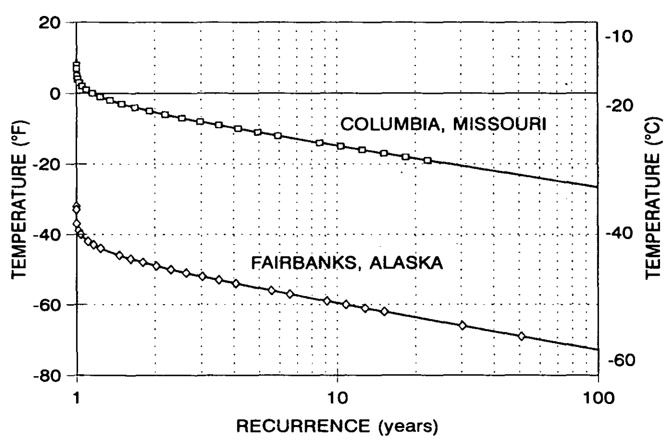

FIGURE 5 Recurrence for minimum daily air temperatures.

TABLE 2 Recurrence Coefficients for Ambient Air Temperature Extremes

Recurrence Period (Years)	Maximum Temperature, Hot Days: Daily Maximums T_{max} °C (°F)	ξ_y	A_d (°F)	B_d (°F)	γ (day)	Diurnal Variations A_h (°F)	ψ (hour)	Minimum Temperatures, Cold Days: Daily Minimums T_{min} °C (°F)	ξ_y	A_d (°F)	B_d (°F)	γ (day)	Diurnal Variations A_h (°F)	ψ (hour)
Fairbanks:														
1	26.7(80)	0.816	29	51	100	15	12	-35.3(-32)	0.438	51	19	104	5	-6
2	30.0(86)	0.878	29	57	100	15	12	-45.0(-49)	0.671	51	-1	104	5	-6
5	31.7(89)	0.908	29	60	100	15	12	-48.3(-55)	0.753	51	-4	104	5	-6
10	32.8(91)	0.928	29	62	100	15	12	-51.1(-60)	0.822	51	-9	104	5	-6
20	33.9(93)	0.949	29	64	100	15	12	-53.3(-64)	0.877	51	-13	104	5	-6
50	35.6(96)	0.980	29	67	100	15	12	-56.1(-69)	0.945	51	-18	104	5	-6
100	36.7(98)	1.000	29	69	100	15	12	-58.3(-73)	1.000	51	-22	104	5	-6
Columbia:														
1	32.2(90)	0.790	20	70	110	15	9	-12.2(10)	-0.363	30	40	110	11	9
2	37.8(100)	0.877	20	79	110	15	9	-20.6(-5)	0.201	30	25	110	11	9
5	39.4(103)	0.910	20	83	110	15	9	-23.9(-11)	0.415	30	19	110	11	9
10	41.1(106)	0.932	20	86	110	15	9	-26.1(-15)	0.557	30	15	110	11	9
20	42.2(108)	0.953	20	88	110	15	9	-27.8(-18)	0.692	30	12	110	11	9
50	43.9(111)	0.980	20	91	110	15	9	-30.6(-23)	0.868	30	7	110	11	9
100	45.6(114)	1.000	20	94	110	15	9	-32.8(-27)	1.000	30	3	110	11	9
	Note: $\phi = -1$ for maximum; $\xi_y = \frac{T_{(d-yr)}}{T_{(d-100yrs)}}$							Note: $\phi=1$ for minimum conditions; $\xi_y=\frac{T_{(d-yr)}}{T_{(d-100yrs)}}$						

a 15-year event. In Columbia, record temperatures were 45°C (113°F), an 80-year event, and −28.3°C (−19°F), a 22-year event.

Solar Radiation

The maximum, average, and minimum daily solar radiation (direct and diffuse) incident on a horizontal surface was examined at each site. In addition, daily solar radiation corresponding to maximum and minimum air temperature days was evaluated. Variations in solar radiation from year to year on a given day indicate fluctuations in factors such as industrial pollution, air turbidity, ozone, and cloud cover. A regression analysis *(30)* in the form of a general Fourier series expansion was selected to fit daily solar; the fit is of the form

$$Q_d = a_0 + \sum_{n=1}^{N} a_n \sin(n\lambda) + \sum_{n=1}^{N} b_n \cos(n\lambda)$$

$$\lambda = 2\pi \frac{(d - \Omega)}{365} \qquad (8)$$

where

Q_d = amount of daily solar radiation incident upon a horizontal surface;
a_0 = average daily solar radiation;
a_n and b_n = the amplitudes of the series;
Ω = lag in days; and
d = day of the year.

Satisfactory convergence was attained with two terms ($N = 2$) for Fairbanks and one term ($N = 1$, $b_1 = 0$) for Columbia. Figures 6 and 7 and Equation 8 coefficients of Table 3 show Fourier series fit for maximum, minimum, and average daily trends in solar radiation throughout the year for Fairbanks and Columbia, respectively. Solar radiation corresponding to maximum $(Q_{d-\max})_{yr}$ and minimum $(Q_{d-\min})_{yr}$ temperature days is assumed appropriate for recurrences (Table 3).

Wind

In Fairbanks from 1952 to 1976, the dominant range of maximum wind speed varied between 0 and 8.9 m/sec (0 and 20 mph) with a daily average maximum of 2.2 m/sec (5 mph). Wind speeds corresponding to maximum and minimum temperature days were predominately less than 2.2 m/sec (5 mph). In Columbia the average wind speed was 4.0 m/sec (8.9 mph) and 4.7 m/sec (10.6 mph) for maximum and minimum temperature days, respectively.

Diurnal Trends and Extremes

For simplicity, wind speed was generally low and therefore considered constant. Precipitation was not included. Therefore, heat transfer energy at any time t during the day is assumed to be a function of ambient air temperature, $[T_h(t)]$, solar radiation $[I_h(t)]$, wind $[v(t)]$, and other factors expressed by

$$q(t) = f[T_h(t); I_h(t); v \ldots] \qquad t = \text{(diurnal)} \qquad (9)$$

The trends show that summer extreme temperatures occur on days 191 and 192 in Fairbanks, Alaska, and days 201 and 202 in Columbia, Missouri. Similarly, winter extremes occur on days 12 to 14 and 8 and 9 for Fairbanks and Columbia, respectively. Diurnal equations for ambient air temperature,

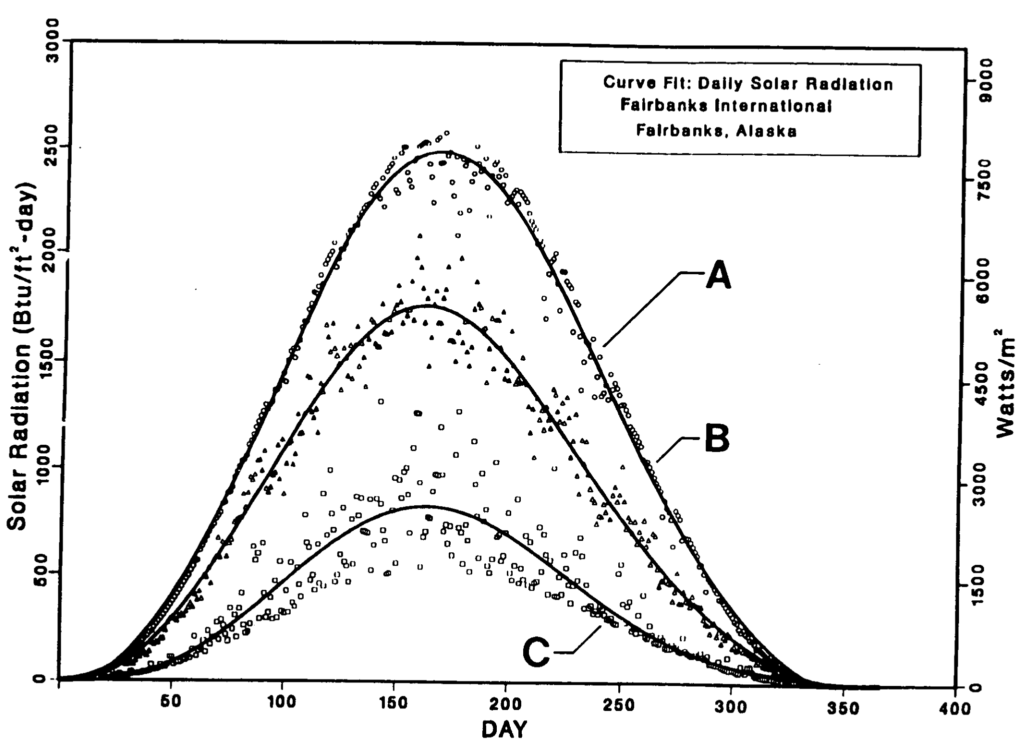

FIGURE 6 Curve fit of daily accumulated solar radiation incident on a horizontal surface, Fairbanks.

corresponding solar radiation, and wind speed for these summer and winter temperature days are presented here.

Air Temperature

Trends in diurnal ambient air temperature are of the form (*2,5*)

$$T_h(t) = A_h \sin 2\pi \frac{(h - \Psi)}{24} + A_d \sin \frac{2\pi(d - \gamma + h/24)}{365} + B_h$$

$$B_h = B_d + \phi A_h \tag{10}$$

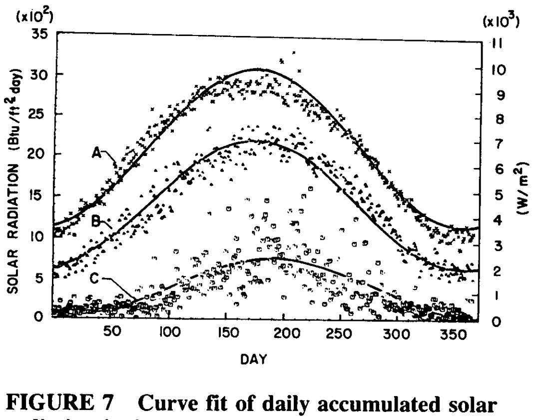

FIGURE 7 Curve fit of daily accumulated solar radiation incident on a horizontal surface, Columbia.

where

T_h = air temperature,
h = hours,
Ψ = hourly lag,
A_h = half the daily temperature range,
B_h = average of daily temperature, and
ϕ = −1 for summer (maximum), 0 for average, and 1 for winter (minimum).

The daily range in temperatures observed at each site is shown in Figure 8. In Fairbanks, ~75 percent of the days had temperature ranges between 5.56°C (10°F) and 13.89°C (25°F). About 82 percent of the days in Columbia had temperature ranges between 8.33°C (15°F) and 16.67°C (30°F). A random sample of the temperature extremes was used to obtain the daily ranges for the summer and winter recurrence equations (Table 2).

Solar Radiation

The intensity of solar radiation received on a horizontal surface at any time t measured from sunrise may be expressed as (*2,3,31*)

$$I_h(t) = 0 \qquad (h_{sr} > h > h_{ss}) \tag{11a}$$

$$I_h(t) = \frac{2Q_d}{d_h} \sin^2 \frac{\pi(h - h_{sr})}{d_h} \qquad (h_{sr} \leq h \leq h_{ss}) \tag{11b}$$

where

Q_d = daily integral of solar radiation given of Equation 8,

TABLE 3 Coefficient for Daily Solar Radiation

Site: Conditions	Coefficients, $W\text{-}h/m^2$ (Btu/ft^2) a_0	a_1	b_1	b_1	b_2	Ω (days)	Valid Range (days)
Fairbanks, Alaska:							
Maximum, $Q_{d\,(max)}$	3482 (1105)	3976 (1262)	142 (45)	63 (20)	-353 (-112)	80	$13 \leq d \leq 338$
Average, $Q_{d\,(avg)}$	2395 (760)	2782 (883)	214 (68)	246 (78)	-290 (-92)	80	$14 \leq d \leq 9$
Minimum, $Q_{d\,(min)}$	1040 (330)	1273 (440)	110 (35)	94 (30)	-253 (-74)	80	$18 \leq d \leq 353$
Max temp days, $(Q_{d\text{-max}})_{yr}$	2962 (940)	3845 (1157)	123 (39)	-9 (-3)	-627 (-199)	80	$19 \leq d \leq 344$
Min temp days, $(Q_{d\text{-min}})_{yr}$	2675 (849)	2899 (920)	79 (25)	139 (44)	-38 (-12)	80	$11 \leq d \leq 332$
Columbia, Missouri:							
Maximum, $Q_{d\,(max)}$	6648 (2110)	3056 (970)	0	0	0	82	$0 \leq d \leq 365$
Average, $Q_{d\,(avg)}$	4439 (1409)	2442 (775)	0	0	0	82	$0 \leq d \leq 365$
Minimum, $Q_{d\,(min)}$	1207 (383)	1084 (344)	0	0	0	99	$0 \leq d \leq 365$
Max temp days, $(Q_{d\text{-max}})_{yr}$	5155 (1636)	2978 (945)	0	0	0	82	$0 \leq d \leq 365$
Min temp days, $(Q_{d\text{-min}})_{yr}$	5318 (1688)	2580 (819)	0	0	0	82	$0 \leq d \leq 365$

h_{sr} and h_{ss} = hour at sunrise and sunset,
d_h = length of day (sunrise to sunset),
h = hour measured from sunrise, and
t = time in hours measured from midnight.

The length of day may be approximated by (*32*)

$$d_h = \frac{2}{15} \text{arc cos} \left[-\tan\phi \tan\delta \right] \tag{12}$$

where ϕ is the geographic latitude in degrees (north positive). The declination of the sun, δ, may be approximated (*33*) by

$$\begin{aligned} \delta = {} & (0.006918 - 0.399912 \cos\Gamma \\ & + 0.070257 \sin\Gamma - 0.006758 \cos 2\Gamma \\ & + 0.000907 \sin 2\Gamma - 0.002697 \cos 3\Gamma \\ & + 0.00148 \sin 3\Gamma) \left(\frac{180}{\pi} \right) \end{aligned}$$

$$\Gamma = \frac{2\pi(d - 1)}{365} \tag{13}$$

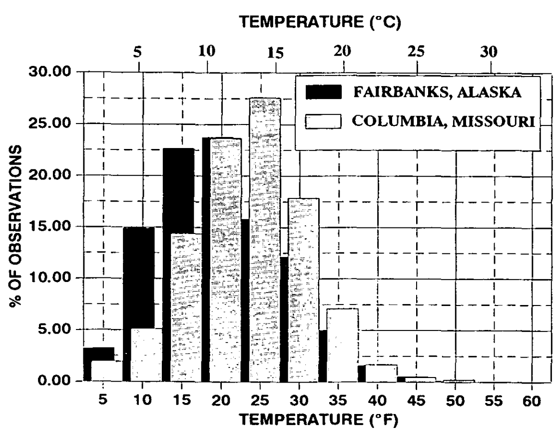

FIGURE 8 Histogram of temperature differentials, Fairbanks and Columbia.

where Γ is day angle and d is day of the year. The latitude, ϕ, is N64°49′ in Fairbanks and N38°45′ in Columbia. Estimations for the declination of the sun and day length at Fairbanks International Airport compared well with ephemeris values.

STRUCTURAL TEMPERATURE CALCULATIONS

Assuming that a highway structure is isotropic with constant thermal properties over length (Figure 1) temperatures will vary with time through the cross section away from the ends in accordance with the familiar heat flow equation:

$$k \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + \overline{Q}(t) = c\rho \frac{\partial T}{\partial t} \tag{14}$$

in which

T = temperature in the structure at x, y, and time t;
$\overline{Q}(t)$ = heat generated per unit volume (e.g., heat of hydration or freeze-thaw);
$\partial^2 T/\partial x^2$, $\partial^2 T/\partial y^2$ = temperature gradients;
$\partial T/\partial t$ = change in temperature; and
k, c, ρ = conductivity, specific heat, and density, respectively.

Table 4 gives thermal properties. Either finite element or finite difference techniques may be used to solve Equation 14 accurately (*2,4,23*).

Mean air temperature $[T_m(d)]$ may be used for initial temperatures, provided analysis is started at least one day earlier, so (*2,4*)

$$T(x, y, 0) = T_m(d) \tag{15a}$$

At any exterior surface exposed to weather, energy is transferred by the Fourier expression of

$$k \frac{\partial T}{\partial x} l_x + k \frac{\partial T}{\partial y} l_y + q(b, t) = 0 \tag{15b}$$

TABLE 4 Material Thermal Properties

Items	Values	References
1. Material Properties:		
Density, ρ	k_g/m^3; (lb/ft^3)	2,4,40,41,42,43
air	1.3 (.081)	
Asphalt	2100 - 2580 (130 - 160)	
Concrete	2243 - 2723 (140 - 170)	
Steel	7834 - 7850 (489 - 490)	
Specific heat, c	J/k_g-°C; $(Btu/lb$-°$F)$	2,4,40,41,42,43
air	922 - 1000 (0.22 - 0.24)	
Asphalt	838 - 1673 (0.20 - 0.40)	
Concrete	922 - 1170 (0.22 - 0.28)	
Steel	464 (0.111)	
Conductivity, k	W/m-°C; $(Btu/ft^2$-hr-°$F)$	2,4,40,41,42,43
air	0.023 - 0.028 (.040 - 0.05)	
Asphalt	0.69 - 0.9 (1.21 - 1.58)	
Concrete	1.4 - 3.7 (0.8 - 2.1)	
Steel	45 - 54 (26 - 31)	
Diffusivity, α = $c\rho/k$	m^2/s; (ft^2/hr)	2,4,40,41,42,43
asphalt	0.2e-06 - 0.5e-06 (0.024 - 0.06)	
concrete	0.5e-06 - 1.5e-06 (0.06 - 0.2)	
steel	4.3e-06 (0.570)	
2. Boundaries Coefficients:		
Film Coefficient, h_c	W/m^2-°C; $(Btu/ft^2$-°$F)$	4,22,35,36.37
Fairbanks wind (0 - 2.2 m/s)	5.68 - 22.2 (1.0 - 3.9)	
Columbia wind (0 - 4.7 m/s)	5.68 - 33.3 (1.0 - 5.87)	
Absorptivity, α		2,4,40,41,42,43,44
asphalt pavements, decks	0.90	
concrete pavements, decks	0.50 - 0.80	
steel decks(rusted)	0.65 - 0.80	
steel decks (new paint)	0.12 - 0.15	
layer of ice	0.3	
layer of snow, frost	0.13	
Emissivity, ϵ		2,4,40,41,42,43,44
asphalt pavts, decks	0.92	
concrete pavts, decks	0.88	
steel decks (rusted)	0.80	
steel decks (new paint)	090 - 0.95	
layer of ice	0.96	
layer of snow, frost	0.91	

where

$\partial T/\partial x$ and $\partial T/\partial y$ = change in temperature in x and y directions,
l_x, l_y = direction cosines at boundary,
$q(b, t)$ = heat flow from exposure, and
b = x,y coordinates along pavement or deck.

At a pavement surface, bridge deck, parapet, or any exterior face exposed to the sun, $q(b,t)$ has contributions of solar flux, $q_s(t)$, convection, $q_c(b,t)$; and thermal radiation, $q_r(b,t)$. At the underside of a bridge, $q(b,t)$ consists of convection and thermal radiation (Figure 1).

The heat transfer components of Equation 15b may be determined from the weather model for air temperature, solar radiation, and wind. Heat gain due to the sun's rays received on a deck or pavement may be expressed daily or hourly by

$$q_s(t) = \alpha I_s(t) \qquad \begin{cases} I_s(t) = Q_d \text{ (Equation 8, annual)} \\ I_s(t) = I_h \text{ (Equation 11, diurnal)} \end{cases} \tag{16}$$

in which α is an absorption coefficient (Table 4) and $I_s(t)$ is the sum of direct and diffuse solar radiation incident upon a horizontal surface. By separating direct and diffuse, any angle of tilt can be accounted for with respect to the horizontal plane (*34*).

Heat transfer by convection is given by Newton's law of cooling, or

$$q_c(b, t) = h_c[T(b, t) - T_a(t)] \tag{17}$$

where

h_c = film coefficient depending on surface texture, slope, and wind speed [h_c is defined in the literature (*22,35–37*)];
$T(b, t)$ = temperature of body boundary, and
$T_a(t)$ = air temperature given by Equation 2 (annual) or Equation 10 (daily).

Heat transfer between the structure and the surrounding atmosphere resulting from long-wave radiation produces a boundary that is nonlinear and time-dependent. It can be modeled by

$$q_r(b, t) = \sigma\varepsilon[\Theta(b, t)^4 - \Theta_a(t)^4] \quad (18)$$

where

σ = Stephen-Boltzman constant = 5.677×10^{-8} W/(m^2 – ^{0}K^4) or 18.891×10^{-8} Btu/(hr – ft^2 – ^{0}K^4),
ε = emissivity coefficient that relates radiation of a gray surface to an ideal black body ($0 \leq \varepsilon \leq 1$), and
$\Theta(b, t)$, $\Theta_a(t)$ = boundary and air temperature in degrees absolute, respectively.

Values are presented in Table 4.

BRIDGE EXPOSURE

AASHTO (*38*) states that "provisions shall be made for stresses or movements resulting from variations in temperature. The rise and fall in temperature shall be fixed for the locality in which the structure is to be constructed and shall be computed from an assumed temperature at the time of erection." The AASHTO provisions give a range of mean bridge temperatures for steel bridges of 83.3°C (150°F) for cold climates and 66.7°C (120°F) for moderate climates. A rise of 17°C (30°F) and fall of 22°C (40°F) of mean bridge temperatures is given for concrete bridges for moderate climates and a rise of 19°C (35°F) and fall of 25°C (45°F) in cold climates.

Mean Bridge Temperatures and Movements

A 1991 National Science Foundation report by Kuppa and Roeder (*6*) provides insight into movements in relation to exposure. Movements were calculated and compared with AASHTO using mean temperatures for three types of bridges at 11 SOLMET climatic sites. Columbia, Missouri, was one of the sites Kuppa and Roeder studied. Linear equations for maximum and minimum mean bridge temperature were expressed as a function of maximum, minimum, and air temperature in the form

$$\Theta = a + bT \quad (19)$$

where

Θ = mean bridge temperature,
a and b = constants, and
T = maximum or minimum air temperature. The equations are based on 50 years of temperature extremes and clear sky solar radiation. Assuming that these linear relationships are valid for return periods, T is replaced by return period temperatures giving summer and winter exposure.

Summer Exposure

Using Table 2, maximum mean bridge temperatures in degrees centrigrade are

$$(\Theta_{max})_{yr} = -3.88 + 1.015\,(T_{max})_{yr} \quad \text{composite} \quad (20a)$$

$$(\Theta_{max})_{yr} = -2.19 + 0.979\,(T_{max})_{yr} \quad \text{box girder} \quad (20b)$$

$$(\Theta_{max})_{yr} = -6.74 + 0.9526\,(T_{max})_{yr} \quad \text{T-beam} \quad (20c)$$

Winter Exposure

Using Table 2, minimum mean bridge temperatures in degrees centrigrade are

$$(\Theta_{min})_{yr} = -6.74 + 1.096\,(T_{min})_{yr} \quad \text{composite} \quad (21a)$$

$$(\Theta_{min})_{yr} = -12.88 + 1.186\,(T_{min})_{yr} \quad \text{Box, T-beam} \quad (21b)$$

The proposed modifications to Kuppa and Roeder's equations (*6*) suggest that 50-year maximum mean bridge temperatures for a composite bridge would be 39.94°C (103.9°F) and 48.4°C (119.2°F) for Fairbanks and Columbia, respectively. The 50-year minimums would be −54.8°C (−66.66°F) for Fairbanks and −26.7°C (−16.1°F) for Columbia. These are temperature ranges of 94.4°C (170°F) for Fairbanks and 75°C (135°F) for Columbia. Kuppa and Roeder suggested 65.4°C (117.7°F) as the mean bridge temperature range for Columbia, but no recurrence was given. The value suggested by AASHTO is 83.3°C (150°F) for a cold climate.

Fairbanks Bridge Temperatures and Stresses

Bridge temperature variations, stresses, and movements in a composite bridge subjected to Fairbanks weather extremes were studied for the effects of varying thermal strain coefficients (*39*). Exposures consisted of three 50-year extreme temperature days in summer and three 50-year extreme temperatures days in winter (*5,39*). The summer maximum concrete deck temperature was 47.2°C (117°F); the maximum temperature differential was 18.9°C (34°F). The winter maximum deck temperature was −16.1°C (3°F). The minimum was −56.1°C (−69°F). The maximum temperature differential for the winter exposure was +1.72°C (3.09°F).

EXAMPLES

Air temperature, solar radiation, and a constant wind velocity are the factors considered. A more refined model should allow for variations in precipitation and wind velocity and the daily range of temperatures. The proposed weather model is based on the idea that maximum temperature gradients occur for exposures involving air temperature extremes.

Consider a 10-year design period in Fairbanks, Alaska. The maximum daily ambient air temperature (Day 191) is obtained by substituting coefficients of Table 2 into Equation 2 to give

$$(T_{d\max})_{10\ \mathrm{yr}} = 62 + 29 \sin\left[\frac{2\pi(d - 100)}{365}\right] \quad ^\circ\mathrm{F}$$

$$= 16.67 + 16.11 \sin\left[\frac{2\pi(d - 100)}{365}\right] \quad ^\circ\mathrm{C}$$

Substituting coefficients of Table 2 into Equation 10 gives the 10-year maximum hourly temperature equation

$$(T_{h-\max})_{10\mathrm{yr}} = 15 \sin \frac{2\pi(h - 12)}{24} + 29 \sin \frac{2\pi(d - 100 + h/24)}{365} + 47\ ^\circ\mathrm{F}$$

$$= 8.33 \sin \frac{2\pi(h - 12)}{24} + 16.11 \sin \frac{2\pi(d - 100 + h/24)}{365} + 8.33\ ^\circ\mathrm{C}$$

The corresponding solar radiation for all ambient air temperature recurrence intervals is given using Equations 11a and 11b

$$I_h(t) = 0 \qquad (h_{sr} > h > h_{ss})$$

$$I_h(t) = \frac{2(Q_{d-\max})_{\mathrm{yr}}}{20.13} \sin^2\left[\frac{\pi(h - h_{sr})}{20.13}\right] \qquad (h_{sr} \le h \le h_{ss})$$

where $(Q_{d-\max})_{\mathrm{yr}}$ is found by substituting the coefficients of Table 3 into Equation 8, to give

$$(Q_{d-\max})_{\mathrm{yr}} = 2962 + 3845 \sin(\Gamma) - 9 \cos(\Gamma) + 123 \sin(2\Gamma) - 627 \cos(2\Gamma) \qquad \mathrm{W-hr/m^2}$$

The equations for minimum periods are obtained by the same procedure.

SUMMARY AND CONCLUSIONS

The discussion provides a rational method for studying the effects of weather extremes on bridges and pavements. The weather exposure models can be incorporated easily into finite element or finite difference programs, or both, to calculate temperature distributions within these structures. A study of a bridge subjected to Fairbanks, Alaska, weather extremes illustrated clearly that the AASHTO provision for thermal loading is inadequate and should be updated to incorporate provisions for design life and thermal gradients.

The method proposed does not account for a random event at any time of year. This type of approach should be developed to provide a rational approach for examining fatigue considerations.

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