

Reliability Based Deterministic Design Approach in Asphalt Pavements

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ABSTRACT: This is a fact that significant level of variability associated with the asphalt pavement design input parameters. Therefore, the estimation of structural reliability has become an important consideration in the design of asphalt pavement structure. Estimation of reliability involves evaluation of damage function which, in turn, depends on expected number of traffic repetitions during design period and the life of pavement life. This paper suggests a simplistic approach to estimate the reliability of asphalt pavements and presented a deterministic way of design procedure at any design reliability level. Finally, the proposed approach has been illustrated through an example problem.

KEYWORDS: Asphalt pavement, pavement design, reliability.

I. OVERVIEW AND OBJECTIVES

The mechanistic-empirical (M-E) asphalt pavement design approach is popularly being used in various guidelines [1-7] and, the fatigue and rutting are generally considered as primary modes of failure. The fatigue and rutting lives are determined using field calibrated regression equations. Simple forms of fatigue and rutting equations can be expressed as given in Eqs. 1 and 2 respectively.

$$N_f = k_1 \left(\frac{1}{\varepsilon_t} \right)^{k_2} \left(\frac{1}{E_1} \right)^{k_3} \quad (1)$$

$$N_r = c_1 \left(\frac{1}{\varepsilon_z} \right)^{c_2} \quad (2)$$

where, N_f and N_r are fatigue and rutting lives of pavement respectively; ε_t is initial critical tensile strain at the bottom of asphalt layer; ε_z is initial critical compressive strain at the top of subgrade; E_1 is the elastic modulus of the asphalt layer; and k_1 , k_2 , k_3 , c_1 and c_2 are regression constants. For a given pavement section and loading conditions, ε_t and ε_z can be estimated through structural analysis of pavement.

The traffic over the design period may be estimated as given in Eq. 3.

$$T = 365 \times A \frac{(1+r)^{yr} - 1}{r} \quad (3)$$

where, T is estimated traffic repetitions; r is annual traffic growth rate; yr is design period in years; and A is numbers of commercial vehicle per day per lane at the time of opening pavement to traffic.

The input variables for estimating traffic (T) and pavement life (N_f or N_r) show significant uncertainty [8-11]. These uncertainties can be incorporated by estimating reliability of the given pavement structure. The structural reliability (R) for a given mode of failure (fatigue or rutting) can be defined as the probability that the repetitions a

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pavement can sustain (N) is greater than the traffic repetitions (T) over the design period. Thus, the reliability R (fatigue or rutting) can be expressed as given in Eq. 4.

$$R = \int_0^1 f_D(d') dd' \quad (4)$$

where, $f_D(d)$ is probability density function (pdf) of damage factor D ; and d' is a variable of integration. The parameter D can be expressed as given in Eq. 5.

$$D = \frac{T}{N} \quad (5)$$

D is a dimensionless parameter and therefore, T and N in Eq. 5 should correspond to a common scale of axle load, which is taken as standard axle load in the present work. However, an in-service pavement undergoes traffic repetitions of different axle loads and thus, the traffic repetitions with different axle loads need to be converted into standard axle repetitions. Various literatures [2,7,12-13] suggest various empirical load equivalency factors for this conversion. The Miner's hypotheses of linear damage accumulation has also been used to evaluate pavement damage under mixed traffic loading [3,14-16], which has been adopted in the present study. According to the Miner's hypothesis, the damage over the design period can be evaluated as given in Eq. 6.

$$D = \sum_{\forall i} \frac{T_i}{N_i} \quad (6)$$

where, T_i and N_i are traffic repetitions and pavement life respectively for the i^{th} axle load. For known present traffic (A_i) of individual axle load, N_i (fatigue or rutting) and T_i can be obtained using Eqs. 1 or 2 and 3 respectively.

Reliability of pavement depends on pdf of D which in turn, depends on pdf of T ($f_T(t)$) and pdf of N ($f_N(n)$). In the present work, a simple methodology has been proposed for estimating reliability making use of Miner's hypothesis. Further, for any given $f_T(t)$ and $f_N(n)$, an analytical solution for pavement life at the design reliability level has been presented. Finally, the proposed methodology has been illustrated through a numerical example.

II. METHODOLOGY DEVELOPMENT

Considering T and N are uncorrelated random variables, $f_D(d)$ for any $f_T(t)$ and $f_N(n)$ can be derived as given in Eq. 7.

$$f_D(d) = \int_0^{\infty} f_N(n) f_T(t = nd) \times |J| dn \quad (7)$$

where, J is Jacobean of inverse transformation. The $f_T(t)$, $f_N(n)$ and their standard deviations can be obtained analytically and/or by simulation for the known variability of inputs. Further, to evaluate the reliability (refer to Eqs. 4 and 7) of pavement, the expected value of T ($E[T]$) and N ($E[N]$) are also to be known. The $E[N]$ in terms of standard axles can be obtained through Eq. 1 or 2 using standard axle load. The $E[T]$ in terms of standard axles can be obtained through Eq. 8.

$$T = N \times \sum_{\forall i} \frac{T_i}{N_i} \quad (8)$$

Eq. 8 is obtained by equating Eqs. 5 and 6. It may be noted that T values for fatigue and rutting case may be different. Another parameter, called as safety margin (S) as expressed in Eq. 9 is extensively being used for reliability estimation [17-21].

$$S = T - N \quad (9)$$

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In a similar way, the pdf of S ($f_S(s)$) can be derived as given in Eq. 10.

$$f_S(s) = \int_0^{\infty} f_N(n) f_T(t = s + n) \times |J| \, dn \quad (10)$$

Thus, the reliability R may also be expressed as given in Eq. 11.

$$R = \int_{-\alpha}^0 f_S(s) \, ds \quad (11)$$

In fact, R value obtained using Eqs. 4 and 11 are the same for any $f_T(t)$ and $f_N(n)$. However, these two equations have certain computational advantages and disadvantages. For example, if both $f_T(t)$ and $f_N(n)$ are normally distributed, $f_S(s)$ is also normally distributed and thus, Eq. 11 becomes computationally easy to handle. In case, both $f_T(t)$ and $f_N(n)$ are log-normally distributed, $f_D(d)$ is also log-normally distributed (since, $\ln D = \ln T - \ln N$) and therefore, Eq. 4 becomes computationally easy to handle.

Reliability R can be computed for various combinations of $f_T(t)$ and $f_N(n)$. In this study, three different combinations have been considered viz. (i) Case I: both $f_T(t)$ and $f_N(n)$ as normal pdf, and Case II: (ii) both $f_T(t)$ and $f_N(n)$ as log-normal pdf. The analytical solution of R (using Eqs. 4 or 11, whichever is suitable) for Case I and Case II has been given in Table 1.

Table 1: Reliability R and Design Life of Pavement N_p at Design Reliability (R_d)

	Case I:	Case II:
Distribution type	$f_T(t)$ and $f_N(n)$: normal	$f_T(t)$ and $f_N(n)$: log-normal
Reliability (R)	$R = \mathbf{N}\left(-\frac{E[S]}{sd_S}\right)$	$R = \mathbf{N}\left(-\frac{E[\ln D]}{sd_{\ln D}}\right)$
	where, $sd_S^2 = sd_N^2 + sd_T^2$; and $E[S] = E[T] - E[N] = T - N$	where, $sd_{\ln D}^2 = sd_{\ln N}^2 + sd_{\ln T}^2$; $sd_{\ln N}^2 = \ln\left(1 + \{sd_N / E[N]\}^2\right)$; $sd_{\ln T}^2 = \ln\left(1 + \{sd_T / E[T]\}^2\right)$; and $E[\ln D] = E[\ln T] - E[\ln N] = \ln(T) - \ln(N)$
Reliability based deterministic design life (N_p)	$N_p = T + Z_{R_d} sd_S$	$N_p = e^{\ln(T) + Z_{R_d} sd_{\ln D}}$

Note: sd_X represents standard deviation of random variable X ; $E[X]$ represents expected value of random variable X ; Z_{R_d} represents standard normal deviate for probability equal to R_d ; and $\mathbf{N}(Z)$ indicates probability for the standard normal deviate Z .

In probabilistic design of pavement, the thickness of design layer(s) is adjusted iteratively so that R becomes equal to the design reliability (R_d). The corresponding pavement life N may be called as design life of pavement

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(N_p) at the given design reliability level. The analytical solution of N_p (fatigue or rutting) is also presented in Table 1.

III. EXAMPLE ANALYSIS

The proposed methodology is elaborated further through a numerical example. First a hypothetical problem is posed and the solution is presented thereafter.

III.(a). PROBLEM DEFINATION

A three layered asphalt pavement has been proposed with asphalt layer thickness of 125 mm and granular layer thickness of 250 mm. The elastic moduli values are 2000, 250 and 60MPa for asphalt, granular and subgrade layers respectively. The Poisson's ratios are 0.30, 0.35 and 0.4 for asphalt, granular and subgrade layers respectively. The coefficients of fatigue (Eq.1) and rutting (Eq. 2) equations

are taken as $k_1=2.21 \times 10^{-4}$, $k_2=3.89$, $k_3=0.854$, $c_1=4.1656 \times 10^{-8}$ and $c_2=4.5337$.

The traffic data at the time of opening traffic to the pavement is given in Table 2. The annual rate of traffic growth (r) is 7.5% and the design period (yr) is 15 years.

Table 2: Traffic Data for Numerical Example Problem

Axle load (kN)	Vehicles/day/lane	Axle load (kN)	Vehicles/day/lane
72	45	84	275
76	80	88	125
80	225	92	50

The coefficient of variation (COV) of traffic, fatigue and rutting life may be taken as 30, 40 and 50% respectively. Considering Case I and Case II as mentioned in previous section, calculate the reliability of the pavement.

III. (b). PROBLEM SOLUTION

For the given pavement section, the critical strains (ϵ_f and ϵ_r) values for each axle load are determined using multilayer linear elastic analysis [22]. N_f , N_r and estimated traffic for each axle load are obtained using Eqs. 1, 2 and 3 respectively. This has been given in Table 3. Accordingly, D and T (in standard axles) are evaluated using Eqs. 6 and 8 respectively, and has been shown in Table 3 itself. Finally, the various parameters for estimating reliability R (refer Table 1) and R values (for Case I and Case II) are computed as presented in Table 3.

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Table 3: Result of Numerical Example Problem.

Axle load (kN)	ϵ_{ti}	ϵ_{zi}	T_i	Fatigue case N_{fi}	Rutting case N_{ri}
72	0.000270	0.000567	0.429×10^6	25.42×10^6	21.86×10^6
76	0.000281	0.000597	0.763×10^6	21.96×10^6	17.20×10^6
80	0.000291	0.000628	2.145×10^6	19.13×10^6	13.71×10^6
84	0.000301	0.000659	2.622×10^6	16.81×10^6	11.05×10^6
88	0.000310	0.000689	1.192×10^6	14.89×10^6	8.99×10^6
92	0.000319	0.000720	0.477×10^6	13.39×10^6	7.39×10^6
$\sum_{\forall i} T_i / N_i (= D) =$				0.43528	0.65477
N (standard axles) =				19.13×10^6	13.71×10^6
T (standard axles) =				8.33×10^6	8.98×10^6
Case I	$E[S] =$			-10.8×10^6	-4.73×10^6
	$sd_s =$			8.05×10^6	7.36×10^6
	$R = \mathbf{N}(-E[S]/sd_s) =$			91.01%	73.98%
Case II	$E[\ln D] =$			-0.8314	-0.4231
	$sd_{\ln D} =$			0.4844	0.5562
	$R = \mathbf{N}(-E[\ln D]/sd_{\ln D}) =$			95.7%	77.66%

IV. CONCLUSIONS

A simple methodology has been presented to estimate the reliability of pavement under mixed loading conditions. This approach can be used to estimate reliability of pavement for any given distributions of $f_T(t)$ and $f_N(n)$. The methodology presented in this paper is general enough and can be used for probabilistic design of pavement structures.

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