Probability and Reliability Aspects in Pavement Engineering

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Abstract. **It is known fact that the structural design of asphalt pavements process is more empirical in nature than the mechanics. Empirical correlation / factors involves in error estimate. Further, while adopting such transfer function, many input parameters are used which are very uncertain and random in nature. Therefore, it is essential to incorporate such uncertainty and considers the probability in the pavement design process. Probabilistically, a pavement is safe when the estimated failure probability or reliability is equal to or higher than the design reliability level. Thus, the consideration of reliability based design of pavement becomes important. Estimated reliability value may be justified provided the proper distributions of pavement performance parameters are adopted including their level of confidence or acceptability. This paper presents the issues related to probability calculation in asphalt pavements. The issues of fatigue and rutting distresses evaluation that involved with many complexities due to materials, structural and loadings conditions, including uncertainty associated with various input parameters are discussed. The resent work also aims to obtain the distributions of performance evaluation parameters and establishes the acceptability of the distributions.**

Keywords**: Asphalt pavement, Fatigue, Rutting, Reliability**

I. INTRODUCTION

The mechanistic-empirical (M-E) design of pavements is widely used in various guidelines (AASHTO, 1993; AI, 1999; Austroads, 2012; APAI, 2008; CAPA, 2006; CDT, 2012; CDT, 2015; DTSD, 2014; FDT, 2012; French, 1997; IDT, 2013; IRC, 2012; MDT, 2015; NCHRP, 2004; SANRA, 2014; Shell, 1978; TRL, 1993; Theyse *et al.*, 1996; WSDOT, 1995). In M-E design approach, a pavement is idealized as multilayered structure and, the fatigue and rutting are considered as two primary modes of structural failure. The number of traffic repetitions (*T*) and the pavement life (*N*) are used to evaluate the pavement performance, either deterministically or probabilistically. Due to large uncertainty associated with *T* and *N*, the deterministic approach seems to be inadequate. While adopting the probabilistic approach, it needs to consider the probability distribution of *T* and *N*, and its distribution parameters. Many researchers (Chou, 1990; Maji and Das, 2008; Pittman, 1996, Kim and Buch, 2003, Kalita and Rajbongshi, 2015; Lu *et al*., 2009; Dilip *et al*., 2013; Stubstad *et al*., 2002; Timm *et al*., 2000). Turochy *et al*. (2005) had reported that *T* and *N* may be considered as normally or lognormally distributed. The issues related to incorporation of reliability in pavement analysis and design is discussed in the present paper. The present work deals with establishing the distribution of *T* and *N*, and subsequently, to present a simple methodology for probabilistic asphalt pavement design, using the derived probability distributions. Fatigue and rutting failures are considered in the present study.

II. BACKGROUND

The structural pavement design process attempts to estimate appropriate pavement design thickness values. It is determined based on the traffic repetitions over the design period (T) and the repetitions a pavement can sustain before failure (N) for a given mode of failure. An asphalt pavement failure primarily happens due to fatigue and rutting. However, the prediction of failure against each mode is very uncertain due to significant inherent variability associated with large number of input parameters (Bush 2004; CRRI 1995; Kim and Buch 2003; Kenis and Wang 2004; Kalita and Rajbongshi, 2015; Noureldin *et al*., 1994; Stubstad *et al*., 2002; Timm *et al*., 1999). Thus, it demands a reliability based design approach, which can accommodate such variability.

To evaluate fatigue or rutting performance, a performance parameter named as damage factor (*D*) can be expressed as,

$$D = \frac{T}{N} \tag{1}$$

The traffic repetitions (T) over the design period can be estimated as,

$$T = 365 \times \frac{(1+r)^n - 1}{r} A \times F \times L \tag{2}$$

where, A is average daily traffic (standard axles) repetitions at the time of opening the pavement to traffic; r is annual traffic growth rate; F is vehicle damage factor; L is lateral distribution factor; and n is the design period in years. The traffic with different axle loads under the mixed loading condition can be converted into the standard axle load by using different empirical load equivalency factors [AI, 1999; IRC, 2012, Huang, 2004; TRL, 1993). The Miner's hypothesis of linear damage accumulation has also been used under mixed traffic loading (Lutes *et al*., 1984; NCHRP, 2004; Sun and Hudson, 2005; Sun *et al*., 2003) and the use of such load equivalency factor can be ignored.

The pavement life N may be fatigue life (N_f) or rutting life (N_r) in terms of number of axle load repetitions (say, standard axle load). N_f and N_r can be predicted as follows (AI, 1999; IRC, 2012; Huang, 2004),

$$N_f = k_1 \times \left(\frac{1}{\varepsilon_t}\right)^{k_2} \times \left(\frac{1}{E_1}\right)^{k_3} \quad (3)$$

$$N_r = c_1 \times \left(\frac{1}{\varepsilon_z}\right)^{c_2} \quad (4)$$

where, ε_t is initial critical horizontal tensile strain at the bottom of asphalt layer; ε_z is initial critical vertical compressive strain at the top of subgrade; E_1 is elastic modulus of the asphalt layer; and k_1, k_2, k_3, c_1 and c_2 are the regression constants. Different literatures have suggested different values of these parameters, and some of them are listed in Table 1. In the present study, the values of k_1, k_2, k_3, c_1 and c_2 are adopted as per Asphalt Institute guidelines.

TABLE 1. Parameters of fatigue and rutting equations.

Organization	k_1	k_2	k_3	c_1	c_2	References
Indian Roads Congress	$2.21\text{x}10^{-4}$	3.89	0.854	$4.166\text{x}10^{-8}$	4.534	(IRC, 2012)
Asphalt Institute	0.0795	3.291	0.854	$1.36\text{x}10^{-9}$	4.477	(AI, 1999; Huang, 2004)
Shell Research	0.0685	5.671	2.363	$6.15\text{x}10^{-7}$	4.0	(Behiry, 2012; Shell, 1978)
US Army Corps of Engineers	497.156	5	2.66	$1.81\text{x}10^{-15}$	6.527	(Behiry, 2012; Huang, 2004)
Belgian Road Research Center	$4.92\text{x}10^{-14}$	4.76	0	$3.05\text{x}10^{-09}$	4.35	(Huang, 2004)
Transport and Road Research Laboratory	$1.66\text{x}10^{-10}$	4.32	0	$1.13\text{x}10^{-06}$	3.75	(Huang, 2004; TRL, 1993)

The strain parameters i.e. ε_t and ε_z may be obtained using response surface methodology as (Engleng, 2016),

$$\varepsilon_t = f_1 + f_2 \ln(E_1) + f_3 \ln(E_2) + f_4 \ln(E_3) + f_5 \ln(h_1) + f_6 \ln(h_2) \quad (5)$$

$$\varepsilon_z = r_1 + r_2 \ln(E_1) + r_3 \ln(E_2) + r_4 \ln(E_3) + r_5 \ln(h_1) + r_6 \ln(h_2) \quad (6)$$

where, E_1, E_2 and E_3 are the modulii of asphalt, granular and subgrade layer respectively in MPa; h_1 and h_2 are the thicknesses of asphalt and granular layer respectively in cm and, f_i and r_i are the model parameters. The f_i, and r_i parameters are tabulated in Table 2.

TABLE 2. Parameters of strain prediction equations.

Parameter	Value	Parameter	Value
f_1	1.453×10^{-03}	r_1	-2.441×10^{-03}
f_2	-7.998×10^{-05}	r_2	$3.20\times x10^{-05}$
f_3	-6.595×10^{-05}	r_3	7.299×10^{-05}
f_4	-1.421×10^{-07}	r_4	9.529×10^{-05}
f_5	-1.060×10^{-04}	r_5	1.07×10^{-04}
f_6	-6.913×10^{-06}	r_6	2.236×10^{-04}

Using Equation 1, the reliability of pavement structure (*R*) can be estimated as,

$$R = \Pr ob.(D < 1) \quad (7)$$

R may be fatigue reliability (R_f) or rutting reliability (R_r) as the case may be. The distribution of *D* can be derived for any known distributions of *T* and *N*. However, it is very complex to derive the distributions of *T* and *N* using probability theorems, as it involves multi layered structural analysis, large number of input variable parameters and the functional forms. As such, Monte Carlo Simulation (MCS) has been used to derive the distributions of *T* and *N*, and is elaborated in the next section.

III. SIMULATION STUDIES

For simulation of T in Equation 2, the variable parameters are adopted as given in Table 3.

TABLE 3. Variable input parameters used for traffic simulation.

Parameter	Mean	Std. dev.
r (%)	7.0	2.0
F	3.0	0.50
L	0.75	0.05

The average daily traffic A = 350 commercial vehicles per day (cvpd) and n = 20 years are considered hypothetically. MCS has been performed generating 1000 data points for each of the random variable which are considered as normally distributed. Accordingly, the distribution and its parameters are determined using maximum likelihood method. This is shown in Figure 1.

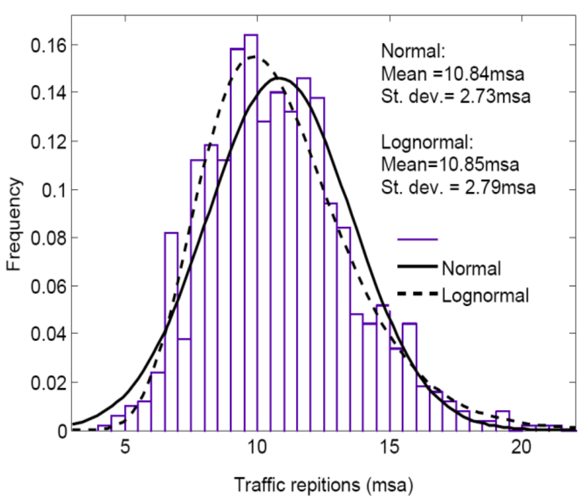

Figure 1. Frequency distribution of traffic parameter.

To judge the acceptability of the distribution, the Chi-square test at 95% confidence level is performed and the result is shown in Table 4.

TABLE 4. Chi-square test statistics for traffic (T) parameter.

Parameter	Normal Dist.	Lognormal Dist.
Mean (msa)	10.84	10.85
Std. dev. (msa)	2.73	2.79
COV (%)	25.17	25.73
Chi-square statistic	37.46	3.50
Prob. of accepting Hypo.	5.0×10^{-7}	0.73
Null Hypothesis	Fail	Pass

In a similar way, MCS has been performed for fatigue (N_f) and rutting (N_r) life parameters using Equations 3 and 4 respectively. Parameters h_1, h_2, E_1, E_2, and E_3 in Equations 5 and 6 are considered as normally distributed as given in Table 5. Therefore, both ε_t and ε_z are also normally distributed.

TABLE 5. Variable input parameters used for pavement life.

Parameter	Mean	Std dev.
h_1 (cm)	15	0.7
h_2 (cm)	20	2.0
E_1 (MPa)	2000	400
E_2 (MPa)	450	100
E_3 (MPa)	80	20

1000 data points are considered for each of the random variable for MCS on N_f. Table 6 shows the results of Chi-square test with 95% confidence level.

TABLE 6. Chi-square test statistics for fatigue life (N_f).

Parameter	Normal Dist.	Lognormal Dist.
Mean (msa)	15.33	15.27
Std. dev. (msa)	8.059	7.62
Chi-square statistic	156.52	10.06
Prob. of accepting Hypo.	1.03×10^{-33}	0.07
Null Hypothesis	Fail	Pass

Following the same procedure in case of N_r, the results of Chi-square test is presented in Table 7.

TABLE 7. Chi-square test statistics for rutting life (Nr).

Parameter	Normal Dist.	Lognormal Dist.
Mean (msa)	18.2	18.2
Std. dev. (msa)	12.2	13.5
Chi-square statistic	83.1	5.2
Prob. of accepting Hypo.	5.6×10^{-21}	0.06
Null Hypothesis	Fail	Pass

IV. PROBABILISTIC DESIGN METHOD

Knowing the distributions of T and N (N_f or N_r as the case may be), and their COV values, the reliability can be estimated for any given set of input. This case, it is observed that T, N_f and N_r may be considered lognormally distributed up to 95% confidence level. Thus, the parameter ln D (= ln T – ln N) in Equation 1 is normally distributed for both fatigue and rutting case. The standard deviation of ln D can be expressed as,

$$S[\ln D]^2 = S[\ln T]^2 + S[\ln N]^2 \qquad (8)$$

where, S[X] represents the standard deviation of random variable X. The standard deviation of ln T or ln N_f or ln N_r can be calculated as,

$$S[\ln X]^2 = \ln(1 + COV_x^2) \qquad (9)$$

Thus, Equation 7 can be rewritten as,

$$R = \Pr ob.(\ln D < 0) \qquad (10)$$

Using Equation 10, and the standard normal distribution table, one can find the R value. That is how a pavement design solution can be obtained iteratively. Otherwise also, the standard normal z-value can be determined corresponding to the design reliability level as given below,

$$Z_R = \left(-\frac{E[\ln D]}{S[\ln D]} \right) \qquad (11)$$

where, expected value E[lnD]=E[lnT] – E[lnN]. Thus, the required pavement life (N^p) (fatigue or rutting life) for the given reliability level can be estimated as,

$$N^p = e^{\ln T + Z_R \times S[\ln D]} \qquad (12)$$

Using Equations 3-6, the estimated pavement life shall be compared with the required life predicted from Equation 12 (fatigue or rutting life as the case may be). That is how a designer can find the design solution without calculating reliability for each trial design alternative.

V. CONLUSIONS

Following conclusions may be drawn from the present studies.

- Traffic repetitions may be considered lognormally distributed with a confidence level of 95%. The fatigue and rutting life of pavements may also be considered as lognormally distributed with a confidence level of 95%.
- Significant variability is observed to be associated with traffic, fatigue and rutting life. This necessitates incorporation of probabilistic approach in flexible pavement design. It is also seen that the level of uncertainty associated is the highest in rutting life, followed by fatigue life and traffic.
- A simple pavement design method has been suggested, where the pavement design solution can be obtained without evaluating the probability by iterative process. The probability based deterministic design concept presented in the study leads to the deterministic design concept and has good prospects to serve as a viable tool to deliver more reliable pavements than the conventional deterministic procedure.

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