Sensitivity Analysis of Design Variables of Flexible Pavement Design Equation in the AASHTO 1993 Design Guide

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Abstract: Although mechanistic-empirical pavement design guide based on National Cooperative Highway Research Program (NCHRP) is available for pavement designers and engineers to design and constructions the pavements, but most of the agencies in the developing countries are still using AASHTO design guide 1993 because of its simplicity. Using this design guide one has to be more careful while selecting the amount of different variables. It is because each of them has different sensitivity and has an impact on the overall pavement design performance. The objectives of this study were to investigate the sensitivity of design variables used in flexible pavement design in AASHTO design guide 1993. Relationships between the pavement structural number (SN) and standard axle load (W18) were studied by varying reliability ($Z_R * S_o$), change in present serviceability index (ΔPSI) and resilient modulus (M_R) of subgrade soil, in a defined range. Statistical tool was used for iteration process and hence determination of influences of these variables. The study reveals that reliability is the most sensitive variable in the design equation, where, axle load depends on the resilient modulus of subgrade. Moreover, a non-linear relationship has been observed between structural number (SN) and axle load.

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1. Introduction

The AASHTO 1993 empirical design procedure was based on the results of the tests conducted during American Association of State Highway Officials (AASHO) road test from 1958-1960 in Ottawa, Illinois. Axle load repetitions of approximately 1.2 million were applied to a unique and specially designed test tracks in the most comprehensive pavement test experiment design ever conducted [1]. Relationship between the input and output parameters were developed using the scientific techniques by modifying the subgrade soil, simple to mixed traffic loading, layer coefficients and by extending the design period. Mechanistic provisions were also incorporated that included classification of subgrade stiffness in terms of resilient modulus and accounting for seasonal variation in the material stiffness. The AASHTO 1993 empirical design procedure has widely been used in pavement designing and its parameters were analyzed for different conditions to ascertain their relative sensitivity [1].

Prozzi et al [2] evaluated the performance of a pavement structure by varying levels of reliability under different traffic, which was designed using AASHTO 1993 Guide. The reliabilities were found higher at standard deviation recommended by AASHTO [2]. AASHTO design approach showed relatively conservative results at low axle load regime. Kamal et al [3] used AASHTO 1993 empirical design procedure to analyze the feasibility of Perpetual Pavements for Developing Countries. Results showed most feasible pavement design using this design equation in terms of life cycle cost. Kamal et al [4] based on AASHTO 1993 design guide, studied the performance of two pavement sections under heavy loading. Section 1 was paved at the start of the winter and Section 2 at the start of the summer. The rate of decrease of air voids in the mix followed a seasonal trend related to temperature [4].

Abaza et al [5] studied the relationship between the accelerated pavement deterioration rates and design pavement strength with two-stage analysis approach. It was found that the stage design strength ratio is relatively low as compared to the corresponding increase in load applications especially at advanced service times. This could be a major contributing factor to the accelerated deterioration of flexible pavement. Therefore, it was recommended to provide initially stronger pavement structures, either designing flexible pavement for a longer design period than the typical 20 years suggested by most design methods or using a higher terminal present serviceability index as in the case of the AASHTO design method [5].

Waseem et al [6] compared pavement analysis results using KENLAYER software, Road Note 31 and AASHTO 1993 Design guide and concluded that the predicted overall structural capacity with Road Note 31 and AASHTO 1993 were in close proximity. However, a significant difference in results was observed when compared with KENLAYER software. ASSHTO 1993 design guide predict rutting while Mechanistic-Empirical methodology predicts fatigue cracking. AASHTO design relates pavement performance to deterioration of ride quality or serviceability over time or applications of traffic loading [7]. Ibrahim [8] studied the effect of overloaded vehicles on the road pavement service life using the AASHTO 1993. Only heavy vehicles were considered to estimate the design ESAL's in accordance with the standard load equivalency factor recommended by 1993 AASHTO Design Guide procedure. He concluded that overloading reduced the pavement service life up to 70% [8]. Davis and Timm revised HMA layer coefficients using the NCHRP test track. The approach contained a flexible pavement design equation with inputs of soil modulus, traffic, structural number, reliability, variability, and change in serviceability. They concluded that a value of 0.54 instead of 0.44 will save about 18% of pavement structure [9].

AASHTO 1993 has widely been used for the structural design of flexible pavement [10] and have the following form:

$$\log_{10}(W_{18}) = Z_R \times S_o + 9.36\times\log_{10}(SN+1) - 0.20 + \frac{\log_{10}\left(\frac{\Delta PSI}{4.2-1.5}\right)}{0.40+\frac{1094}{(SN+1)^{5.19}}} + 2.32\times\log_{10}(M_R) - 8.07 \quad (1)$$

W18 = Predicted number of 80 kN (18,000 lb.) ESALs
Z_R = Reliability
S_o = Overall standard deviation
SN = Structural Number
ΔPSI = Loss in Serviceability
M_R = Resilient Modulus (psi)

Reliability (Z_R) is the probability that a pavement section designed will perform satisfactorily over the traffic and environment conditions for the design period. Equation 2 determines the reliability of pavements in terms of present serviceability index [11].

$$p_t = c_o - (c_o - c_1)\left[\frac{W_t}{\rho}\right]\beta \quad (2)$$

Where p_t, c_o, c_1, W_t, ρ and β are the present serviceability at time t ($c_1 \leq p_t \leq c_0$), initial and terminal serviceability values, accumulated axle load and the regression parameters respectively. The overall standard deviation (S_o) is a factor that takes into accounts the designers ability to estimate future 18-kip equivalent axle load. Structural Number (SN) is a number which represents the overall pavement structural requirements. Loss in Serviceability (ΔPSI) is the amount of serviceability loss over the life of pavement. Resilient Modulus (M_R) reflects the engineering properties of the subgrade soil. M_R can be calculated using AASHTO test method T274 [12]. Empirical relationships can also used to determine M_R from CBR values.

2. Methodology

A sizeable range of AASHTO 1993 Design equation variables were studied keeping in view that a significant effect on relationships between structural number of a pavement and W18 can be investigated. The structural number was chosen from 1 to 6 with a unit increment and reported in Table 1. This range precisely covers all types and conditions of highway pavement and parking lot thicknesses. Runway or the taxiway pavements were covered for the time being because it may complicate the study objective. Five reliability levels from 80 to 100 percent and Z_R*S_o from -1.5 to -0.37 were chosen that covers most of the design cases. Net present serviceability was taken from 0.5 to 2.5 with an increment of 0.5. These values also covers the entire serviceability conditions a pavement from newly constructed smooth pavement to deteriorated failed pavement. Similarly, five resilient modulus values were chosen covering soft to very stiff soils. Axle load in terms of W18 were calculated for each set of conditions.

Table 1. Selected of parameters of AASHTO 1993 design guide equation

Reliability	Z_R	S_o	Z_R*S_o	Δ PSI	(M_R)
100	-3.75	0.40	-1.50	2.5	5,000
95	-1.65	0.41	-0.67	2.0	10,000
90	-1.28	0.42	-0.54	1.5	15,000
85	-1.04	0.43	-0.45	1.0	20,000
80	-0.84	0.44	-0.37	0.5	25,000

Influence of three variables Z_R*S_o, ΔPSI and M_R on W18 at each structural number were calculated using the 1993 AASHTO design equation. Step wise iteration process was carried out to determine the effect of individual parameter by keeping other parameters constants. For example in first trial at Z_R*S_o of -1.5, the value of Δ PSI and M_R was fixed at

2.5 and 5,000 respectively and in second trial M_R was selected as 10,000. Similarly, M_R values were varied from 5,000 to 25,000 at each Δ PSI and Z_R*S_o levels. Data obtained from excel sheets were summarized and relationships were then determined between the structural numbers and W18 at each condition. Results were presented in graphs for the ease of readers.

3. Results and Discussion

3.1 Reliability: Relationship between SN and W18 at five different Z_R*S_o levels were determined and plotted as shown in Fig 1. Results showed non-linear trends for the entire range of data. No significant effects were observed up to structural number of 3. It means the AASHTO equation does predict well the effects of different variables for a pavement having less than 03 structural numbers. Power curve equation were obtained from the plots which reveals that slope coefficient remains the same for entire range of Z_R*S_o. However intercept coefficient gradually increases with an increase in the values of Z_R*S_o.

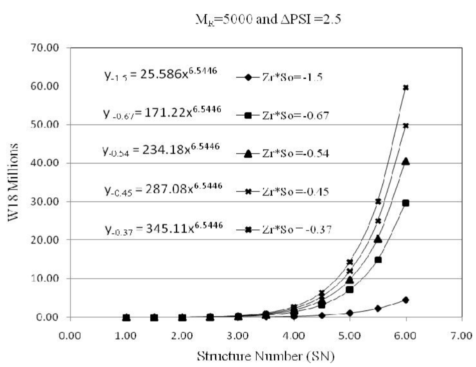

Figure 1. Influence of Z_R*S_o on W18 – SN relationship

Fig 1 shows that the intercept coefficient increases for Z_R*S_o value ranging from -1.5 to -0.67 (indicative of the decrease in the reliability from 100 to 95) to almost about 570% but from -0.67 to -0.37 this coefficient decreases drastically. It means at higher Z_R*S_o value (indicative of the decrease in the reliability R) intercept coefficient starts decreasing. And also higher Z_R*S_o values have no significant effect on this relationship. To predict the effect of change of Z_R*S_o on W18-SN relationship, the intercept coefficient (y-axis) were plotted against each Z_R*S_o level (x-axis) and following best fit trend line equation was obtained;

$$y = 260.62x + 404.45$$

R^2=0.88 **(3)**

One can determined the effect of change of Z_R*S_o on W18-SN relationship using the above relationship.

3.2 Resilient Modulus

Effect of M_R was worked out at different Z_R*S_o and ΔPSI using statistical tools. The data sheets were developed to analyze the effect of an individual increase in the M_R value. Plots in Figure shows the influence of M_R on W18 at different levels of Z_R*S_o and ΔPSI. One can observe that an increase in W18 from stiff to weaker soils for SN up to 4 is not significant. Beyond this structural number an abrupt increase in W18 occurs. Also intercept coefficient is sensitive of resilient modulus of soil. Analysis of the intercept coefficient shows that an increase in M_R value from 5,000 (indicative of typically the poor sub grade soil consisting of fine silty sands, and organic soils) to 10,000 (indicative of typically fair sub grade soil having CBR of 5-9 consisting of clayey gravels and clayey sands) the intercept coefficient increases to almost 400%. At higher M_R values intercept coefficient is not a sensitive number, which means the higher M_R values has no significant effect on these relationships.

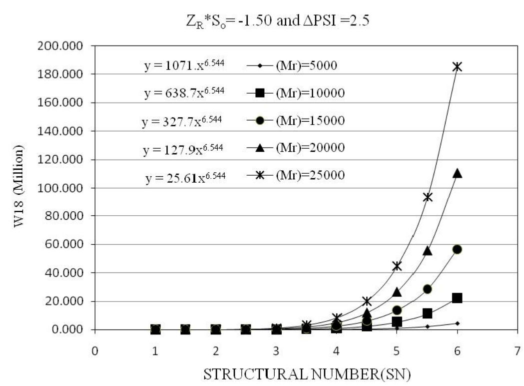

Figure2. Influence of M_R on W18 – SN relationship

3.3 Net Present Serviceability

Fig 3 shows the influence of ΔPSI on the W18-SN relationship at Z_R*S_0 = -1.5 and resilient modulus of 10,000. Non-linear trends were observed for the entire range of ΔPSI. Both the slope and intercept coefficients were sensitive to change in ΔPSI values. Analysis of the intercept coefficient (multiple coefficient of the relationship) shows that with a decrease in the value of ΔPSI from 2.5 to 2 (indicative of the decrease in the loss of the serviceability from initial serviceability 'p_o' to terminal serviceability 'p_t') the intercept coefficient (power coefficient of the relationship) increases to about 10.5%. At the same time, the power coefficient of the equation increases as we increase the ΔPSI values. It is understood that the power component is more effective that multiple. Further percentage change ΔPSI was plotted against percentage change in both the power and multiple coefficients as shown in Figure 4. One can see the same spread (different signs) in percentage variations on the plot. Knowing that the power coefficient is more critical than multiple it can be revealed that higher ΔPSI has higher impact on the W18-SN relationship at any reliability level.

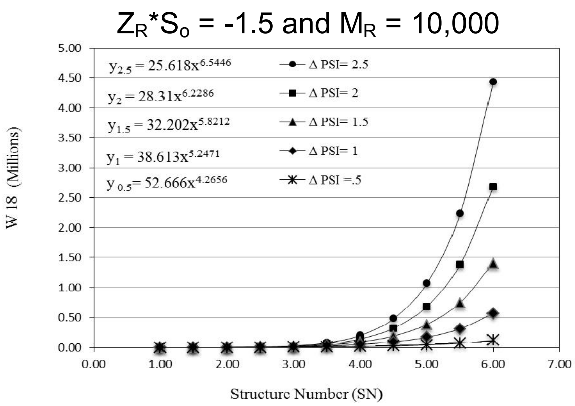

Figure 3. Influence of Δ PSI on W18 – SN relationship

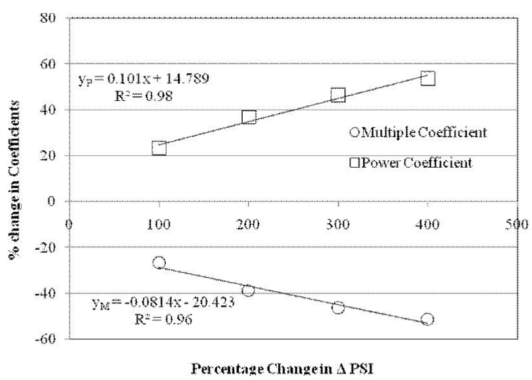

Figure 4. Influence of ΔPSI on sensitivity of W18 – SN relationship Coefficients

3.4 Sensitivity Analysis

Sensitivity of each variable in flexible pavement equation of AASHTO 1993 Design Guide was investigated using statistical tools and percentage change of individual variable were plotted against percentage change in W18. Figure 5 shows plots between % change in Z_R*S_o – W18, ΔPSI – W18 and M_R – W18 at a typical structure number of five and measures the relative sensitivity of the variables. Nonlinear trends can be observed in each plot. General trends support the fact that design load increases with a percentage increase in the variable. This compares and ascertains as Z_R*S_o the most sensitive factor in the AASHTO 1993 design guide equation.

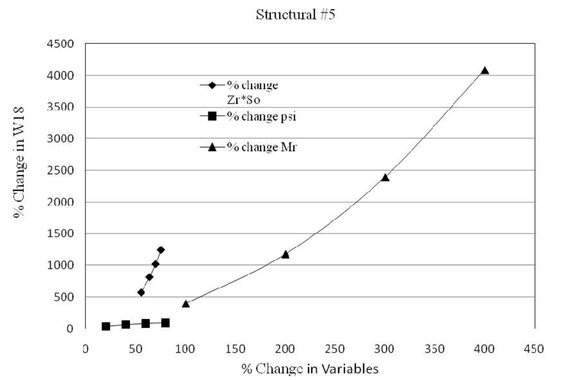

Figure 5. Comparison of the influence of all variables

4. Conclusions

The following conclusions have been drawn from this study:

1. Relationships among the parameters of AASHTO 1993 Design Guide equation were nonlinear.
2. Z_R * S_o predicts uncertainty in pavement performance and future ESALs and is the most sensitive parameter in AASHTO 1993 Design Guide. Change in PSI that relates pavement riding quality is least sensitive variable.
3. SN-W18 relationship is sensitive for low subgrade resilient modulus values and ΔPSI level.

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