Parametric Sensitivity Study of the AASHTO Flexible Pavement Design Equation

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Parametric Sensitivity Study of the AASHTO Flexible Pavement Design Equation

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The influence of design variables on the change in traffic capacity used for flexible highway pavement designed by the AASHTO procedure was studied. The change in the total equivalent single axle load (ESAL) that a pavement can carry due to a change in reliability level, overall standard deviation, structural number, drop in serviceability index and the subgrade modulus of resilience, has been individually investigated. The AASHTO equation was simplified into different models that give the relationship between the change in each variable and the change in total ESAL to be carried by the highway pavement. The parametric sensitivity study showed that the structural number of the construction material and the subgrade modulus of resilience have the greatest effect on the load carrying capacity; whereas the change in serviceability index, reliability and overall standard deviation levels have relatively less effect.

Keywords: Flexible pavement design; AASHTO equation; Influence of variables.

INTRODUCTION

There are several accepted procedures for flexible pavement design. Examples of these procedures include: California (Hveem) method[1], the Asphalt Institute method[2], and the widely known method of the American Association of State Highway and Transportation Officials (AASHTO)[3]. In this method the cumulative number of equivalent 18-kip single axle load (ESAL) is correlated to two types of variables. The first type has to be selected by the designer within a suggested AASHTO range. This type includes reliability level, overall standard deviation and the loss in serviceability index. The second type of variables have to be inescapably determined, such as the construction material (layer coefficients) and roadbed properties.

The aims of this study were: (a) to address the impact of each variable change (individually) on the load carrying capacity of the pavement (total ESAL); and (b) to establish simple and approximate models that describe the relationships between the total ESAL and each individual variable.

LITERATURE REVIEW

The AASHTO equation have been analyzed by many researchers[4-9]. Following is a brief review of five examples of studies that have almost the same goals of this study.

Gilbert and Thomas[4] have evaluated the AASHTO flexible pavement design equation using mechanistic approach. Pavement sections with various layer properties, road bed modulii and traffic volumes were designed using the 1986 AASHTO procedure. Mechanistic response in terms of deflection, stresses, and strains were calculated. The evaluation addressed three features of the AASHTO design method: the structural number, the layer coefficient and the main design equation. The study showed that the role of roadbed resilient modulus in the equation is not accurate and that, for any pavement layer, the layer coefficient is not a simple function of the modulus value of that layer. It is a function of all layer thickness and properties.

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Noureldin *et al*[5] have shown an explicit quantification of the variables that appear in the AASHTO equation in terms of their mean values and their covariances (COVs). The study showed that COVs of paving layer thickness and material properties, for which ample data are available, can be used by experienced pavement engineers to make realistic estimations, that are almost as good as the values that can be measured. The COVs for the independent variables in the AASHTO equation were then shown to be a practical tool for quantifying the variability in flexible pavement performance and estimate the standard deviation of that performance.

Brian and Zollinger[6] have conducted a sensitivity analysis of selected design inputs two Kentucky pavements with different design criteria. The purpose of that study was to determine which inputs have the greatest effect on the prediction of the design life. The sensitivity study was conducted by varying the chosen design inputs by plus or minus the assigned coefficient of variation from the mean level of the design input. The design inputs were the subgrade strength, the traffic level in equivalent single axle load per year, the surface layer modulus and the surface thickness. The sensitivity analysis for the pavements under investigation indicated that with low traffic and weak subgrade, the flexible pavement design is moderately sensitive to changes in subgrade modulus. Allowable traffic and surface modulus, however, were found much sensitive to changes in surface thickness.

Baus and Fogg[7] have reported a significance study for the AASHTO flexible pavement design equation. They provided an insight into the relative change in required thickness of pavement structure that would result from errors in input parameters. The study results indicated that variation in modulus of subgrade resilience has the most pronounced effect on the structural number. Variation in the total number of equivalent single axle load has a lesser effect. Variation in the overall standard deviation has minimal effect on the structural number. Selection of higher reliability values will result in significantly higher values of structural number.

Coree and White[8] have criticized the AASHTO design procedure. They claimed that a considerable disagreement is apparent about the definition and the recommended method of measurement of layer coefficients. They contend that layer coefficients are no more than regression coefficients, with no ascribable physical or engineering meaning other than being a scaling or normalizing constant. They expressed their fear that the application of the principles of reliability in the AASHTO model is fraught with problems during implementation. They recommended that the AASHTO Road Test data should be scrutinized and reanalyzed in the light of newer pavement technology and new models have to be developed.

PRINCIPLES OF ANALYSIS

The concept of this paper came from the nature of the AASHTO equation used for design of highway flexible pavement. The equation is based largely on algorithms developed from the findings of the AASHTO road test completed in May 1962. The latest 1986 AASHTO guide have been expanded to accommodate different input parameters. The design equation took the form:

$$\log_{10}(W_{18}) = Z_R S_O + 9.36\log_{10}(SN+1) - 0.2 + \frac{\log_{10}[\Delta PSI/(4.2-1.5)]}{0.4+[1094/(SN+1)^{5.19}]} + 2.32\log_{10} M_r - 8.07 \quad (1)$$

where W_{18} is predicted number of 18 000 lb (80kN) single axle load applications; Z_R, standard normal deviation for a given reliability; S_O, overall standard deviation; SN, structural number indicative of the total pavement thickness; $\Delta PSI = Pi - Pt$; Pi, initial serviceability index; Pt, terminal serviceability index; and M_r the resilience modulus in lb/in^2.

In order to perform sensitivity analysis procedure for a variable, so that it's impact on ESAL is analyzed; two methods may be followed. The first method is by providing the fixed values of the remaining variables in equation (1) itself, while varying only one of the variables. Such type of analysis could be easily done on computer. The second method is by manipulating equation (1) so that the least of variables are incorporated as described here.

The AASHTO equation could be written as:

$$\log_{10}(W_{18}) = X + C$$

where X is the variable under study; and C a constant that accommodates for other variables.

For different values of the changed variable (X), this equation could be manipulated as:

$$\log_{10}(W_{18})_1 = X_1 + C$$

$$\log_{10}(W_{18})_2 = X_2 + C$$

where X_1 and X_2 are two different values of the changed variable in the equation and $(W_{18})_1$ and $(W_{18})_2$ are the corresponding numbers of the 18-kip axle load applications for the new values of the changing variable.

By subtracting the above two equations

$$\log(W_{18})_2 - \log(W_{18})_1 = X_2 - X_1$$

or

$$\log\frac{(W_{18})_2}{(W_{18})_1} = X_2 - X_1 \quad (2)$$

Equation(2) allows examining the effect of change in each variable on the change in total ESAL as represented by W_{18}.

ANALYSIS AND DISCUSSION

The factors considered in the AASHTO procedure for the design, as presented in the 1986 guide, are:

1-Traffic, represented by the total Equivalent Single Axle Load (ESAL), or the (W_{18}),

2- Reliability (R) and Overall Standard Deviation (S_O),

3- Material of construction represented by indicative number of the total pavement thickness (Structural Number SN),

4- Pavement performance represented by the Loss in Present Serviceability Index (ΔPSI),

5-Roadbed soil (subgrade material) represented by the Modulus of Resilience (M_r)

The effect of variation of these factors on the total ESAL to be carried by the pavement will be discussed hereafter according to the previous order (their order in the AASHTO equation).

Variation in Reliability

Reliability (R) is a way of incorporating some degree of certainty into the design process to ensure that various design alternatives will last the analysis period[3]. A design of higher reliability necessitates an increase in the traffic level used in the analysis. This results in an increased pavement layer thickness to fulfill the pavement's intended function. Reliability effect has been studied by Brian and Zollinger[6] and James[11].

The main AASHTO equation could be re-written as:

$$\log(W_{18}) = Z_R S_O + C$$

It can be seen from the equation that reliability is represented by it's standard normal deviation Z_R. At a certain level of overall standard deviation, a relationship between the change in reliability and the corresponding change in total ESAL could be derived as

$$\log(W_{18})_1 = Z_{R_1} S_O + C$$

$$\log(W_{18})_2 = Z_{R_2} S_O + C$$

$$\log(W_{18})_2 - \log(W_{18})_1 = S_O\left(Z_{R_2} - Z_{R_1}\right)$$

$$\log\frac{(W_{18})_2}{(W_{18})_1} = S_O\left(Z_{R_2} - Z_{R_1}\right)$$

$$\frac{(W_{18})_2}{(W_{18})_1} = 10^{S_O\left(Z_{R_2} - Z_{R_1}\right)} \quad (3)$$

Reliability range is between 50% and 99.99%, *ie*, Z_R ranges between 0.0 and 3.09. The AASHTO recommended a range

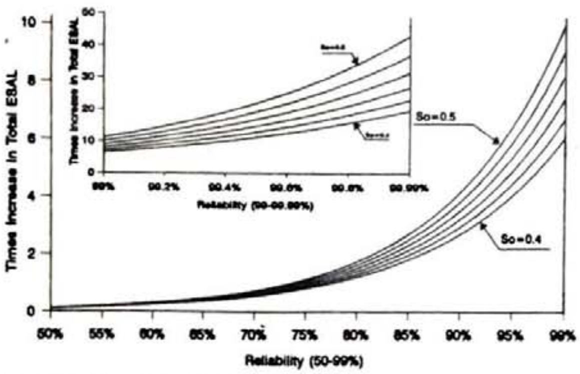

Fig 1 Effect of reliability on total ESAL

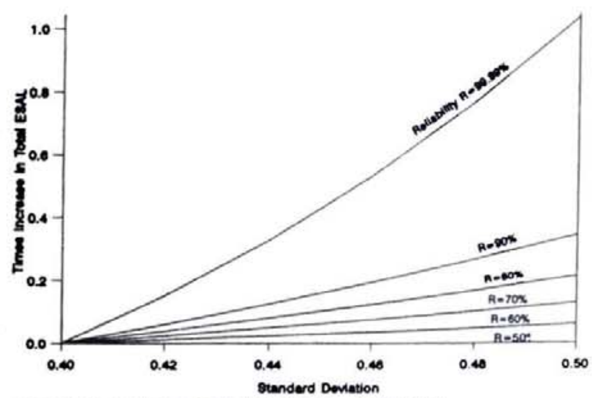

Fig 2 Effect of standard deviation on total ESAL

of overall standard deviation (S_O) between 0.4 and 0.5 for flexible pavement. By substituting different Z_R and S_O values, within the ranges mentioned above, fig 1 was produced to represent the relationship shown in equation 3. The figure shows the relationship between the change in total ESAL due to change in reliability for reliability range between 50% and 99% and for S_O values between 0.4 and 0.5. The subchart inside the figure shows the same relationship for reliability range between 99% and 99.99%. It can be seen from both figures that the change in ESAL is significantly affected by the change in reliability especially at higher levels (99% to 99.99%).

Variation on Overall Standard Deviation

The overall standard deviation identifies the variance estimates for the factors associated with the performance prediction of paving material and the standard deviation of the predicted amount of traffic that will use the facility[5]. Following the same steps mentioned previously in reliability, the following relationship between S_O and the total W_{18} could be derived:

$$\log \frac{(W_{18})_2}{(W_{18})_1} = Z_R \left(S_{O_2} - S_{O_1}\right)$$

$$\frac{(W_{18})_2}{(W_{18})_1} = 10^{Z_R \left(S_{O_2} - S_{O_1}\right)} \qquad (4)$$

Equation (4) represents the real relationship between the change in overall standard deviation and the change in total ESAL. The equation is of the type $y = 10^{ax}$. It is appropriate to obtain the values of y by changing x values. In order to simplify this relationship, different values were assigned for S_O and the best fit linear regression line was drawn (as shown in Fig 2) for reliability levels between 50% and 99.99%, the models obtained were:

$Y = -0.240 + 0.5999\,X$ for reliability = 60% (R^2=0.99)

$Y = -0.514 + 1.282\,X$ for reliability = 70% (R^2 =0.99)

$Y = -0.857 + 2.130\,X$ for reliability = 80% (R^2 = 0.98)

$Y = -1.379 + 3.430\,X$ for reliability = 90% (R^2 = 0.97)

$Y = -4.178 + 10.320\,X$ for reliability = 99.99% (R^2= 0.96)

where X is overall standard deviation (S_O); and Y times change in ESAL due to a change in (S_O) from 0.4 to a value = X.

It should be noted that the horizontal axis in the figure represents the values of (S_O) within the range from 0.4 to 0.5, *ie*, a percent increase from 0.0 to 25. It can be seen from the figure that the effect of (S_O) on total ESAL (although it is relatively low) is highly dependent on the reliability level.

Variation in Structural Number

The structural number is a measure of the pavement strength. An increase in this number will allow for an increase in the total ESAL load. The relationship between the change in these two variables could be derived following the general principles of analysis as

$$\log \frac{(W_{18})_2}{(W_{18})_1}\ 9.36\log \frac{(SN_2+1)}{(SN_1+1)} + \log\ \frac{\Delta\,PSI}{2.7}\left(\frac{X_1 - X_2}{X_1 X_2}\right) \qquad (5)$$

in which

$$X_1 = 0.4 + [1094/(SN_1 + 1)^{5.19}]$$
$$X_2 = 0.4 + [1094/(SN_2 + 1)^{5.19}]$$

For $SN_2 > SN_1$ the value $X_1 - X_2$ will be positive with a result that the changed total ESAL will increase as the structural number increases depending on the level of $\Delta\,PSI$

Equation 5 represents the real relationship between the change in structural number and the change in total ESAL. In order to obtain a simplified relationship, a power regression model was fitted to the data obtained from assigning different values for SN at different $\Delta\,PSI$ levels, the following models were obtained:

$Y = 0.0485X^{4.23}$ for $\Delta PSI = 0.5$ (R^2 = 0.70)

$Y = 0.0463X^{5.53}$ for $\Delta PSI = 1.0$ (R^2 = 0.68)

$Y = 0.0447\,X^{6.28}$ for $\Delta PSI = 1.5$ (R^2= 0.65)

$Y = 0.0439\,X^{6.82}$ for $\Delta PSI = 2.0$ (R^2 = 0.64)

$Y = 0.0431\,X^{7.24}$ for $\Delta PSI = 2.5$ (R^2 = 0.63)

where X is structural number (SN) ; and Y is times change in ESAL due to a change in SN from 2 to a value = X. Fig 3 shows the relationship between SN and total ESAL for different ΔPSI levels. This relationship has been magnified for lower SN values and shown in the small figure inside the main one. It can be seen from both figures that the change in structural number has a significant influence on the change in total ESAL especially at higher levels of ΔPSI.

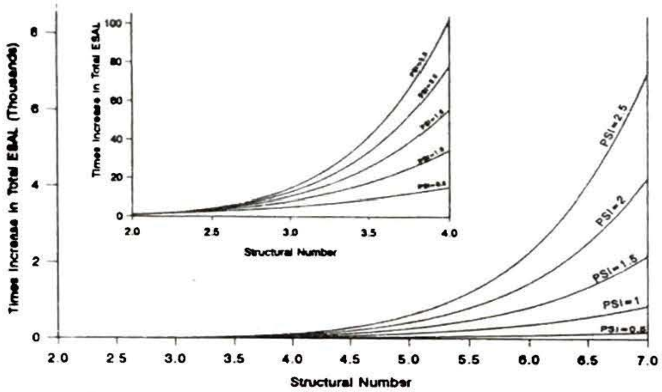

Fig 3 Effect of structural number on total ESAL

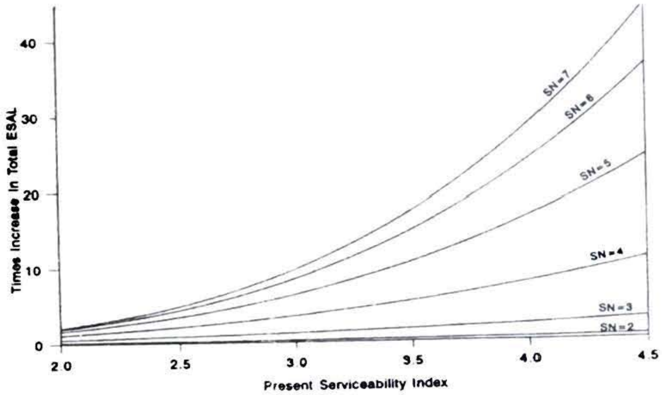

Fig 4 Effect of present serviceability index on total ESAL

Variation in Loss of Serviceability Index

The loss in serviceability index (Δ *PSI*) is the difference between the terminal serviceability (*Pt*) and the initial serviceability (*Pi*) indices. The value of *Pi* established for the AASHTO road test conditions for flexible pavement was 4.2. An index of 2.5 or 3 is often suggested for design of major highways and a value of 2.0 for highways of lower classification. For relatively minor highways where economic factors dictate lower costs, a value of *Pt* equals 1.5 may be used. Based on the above values of *Pt* and *Pi*, Δ *PSI* may range from 0.0 to 2.5. The relationship between Δ *PSI* and the total ESAL could be derived from the main equation as

$$\log\left(W_{18}\right)_1 = C + \frac{\log \frac{(\Delta PSI)_1}{2.7}}{0.4 + [1094/(SN+1)^{5.19}]}$$

$$\log\left(W_{18}\right)_2 = C + \frac{\log \frac{(\Delta PSI)_2}{2.7}}{0.4 + [1094/(SN+1)^{5.19}]}$$

thus :

$$\log \frac{(W_{18})_2}{(W_{18})_1} = \frac{\log \frac{(\Delta PSI)_2}{(\Delta PSI)_1}}{0.4 + [1094/(SN+1)^{5.19}]} \quad (6)$$

Equation (6) shows the real relationship between the change in Δ PSI and the change in total ESAL. In order to obtain a simplified relationship a power regression model was fitted to the data obtained from assigning different Δ PSI values at selected SN levels. The following models were obtained.

$Y = 0.0049\ X^{1.05}$ for $SN = 2$ ($R^2 = 0.97$)

$Y = 0.0165\ X^{1.39}$ for $SN = 3$ ($R^2 = 0.99$)

$Y = 0.0275\ X^{1.892}$ for $SN = 4$ ($R^2 = 0.98$)

$Y = 0.0339\ X^{2.27}$ for $SN = 5$ ($R^2 = 0.96$)

$Y = 0.0367\ X^{2.47}$ for $SN = 6$ ($R^2 = 0.94$)

$Y = 0.0378\ X^{2.58}$ for $SN = 7$ ($R^2 = 0.93$)

where X is present serviceability index (PSI); Y, times increase in total ESAL due to a change in *PSI* from 2 to a value = X.

Fig 4 shows the relationship between the change in *PSI* and the change in total ESAL for different *SN* levels. The figure indicates that as the present serviceability index increases, the change in total ESAL increases especially at higher *SN* values. Increasing *PSI* means improving the pavement capability to carry extra ESAL which allows for more traffic to pass over the road before it reaches it's terminal level.

Variation in Modulus of Resilience

The modulus of resilience is a measure of subgrade strength. It is the primary subgrade property of interest in the structural pavement design. Keven and Marshal[12] have shown a method to estimate soil resilient modulus for flexible pavement design. The modulus value could either be determined or correlated to other soil properties[3,13]. The main AASHTO equation could be re-written as

$$\log\left(W_{18}\right) = 2.32 \log M_r + C$$

for a change in the modulus magnitude from M_{r1} to M_{r2}, a change in (W_{18}) from $(W_{18})_1$ to $(W_{18})_2$ could be derived as

$$\log \frac{\left(W_{18}\right)_2}{\left(W_{18}\right)_1} = 2.32 \log \frac{M_{r2}}{M_{r1}}$$

$$\frac{\left(W_{18}\right)_2}{\left(W_{18}\right)_1} = 10^{2.32 \log \frac{M_{r2}}{M_{r1}}} \quad (7)$$

Equation (7) indicates that an exponential relationship exists between modulus of resilience and the change in total ESAL. Fig 5 shows this relationship. As can be seen from the figure the effect of change in modulus of resilience on the change in total ESAL is not dependent on the level of other variables in the main equation.

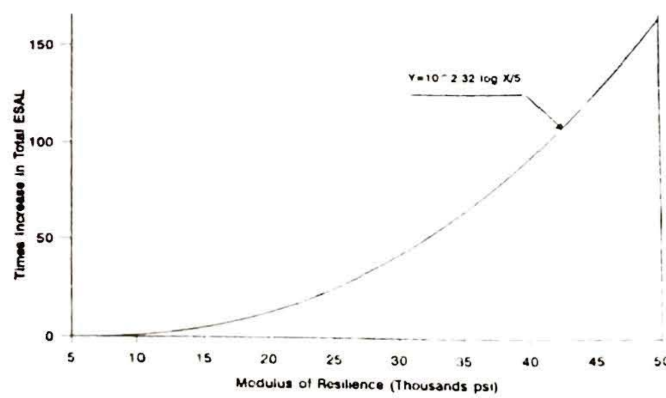

Fig 5 Effect of modulus of resilience on total ESAL

SUMMARY AND CONCLUSIONS

The analysis has highlighted some points that could hardly be traced from the general look at the AASHTO design equation. The figures and models shown in the study may aid the designer to easily select design alternatives. For instance, increasing the structural number from 2 to 4 will increase the total ESAL that can be carried by the pavement by about 13 times at $\Delta PSI = 0.5$. Meanwhile this amount of increase will be about 8245 times if the allowable loss in *PSI* is increased to 2.5 instead of 0.5. The same applies for the case of modulus of resilience where an increase in this modulus by a factor of 2 (say from 5000 to 10 000 psi) will allow for an increase in the total ESAL about 5 times. This increase reaches 209 times if the modulus is increased by a factor of 10 (say from 5000 to 50 000 psi). More indications could be concluded from the study having the general form such as :

1.Variation of the structural number of the construction material has the greatest effect on the load carrying capacity. This effect is dependent on the allowable loss in the serviceability index.

2.Variation in the subgrade modulus of resilience has the second greatest effect on the load carrying capacity. This effect is independent of other variables.

3.Variation in reliability, overall standard deviation and serviceability index levels have relatively less effect on the total ESAL to be carried by the pavement.

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