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Analysis of experimental pavement failure data using duration models

by Jorge A Prozzi[1] and Samer Madanat[2]

Abstract

Predicting pavement performance under the combined action of traffic and the environment provides valuable information to a highway agency. The estimation of the time at which the pavement conditions will fall below an acceptable level (failure) is essential to program maintenance and rehabilitation works and for budgetary purposes. However, the failure time of a pavement is a highly variable event; terminal conditions will be reached at different times at various locations along a homogeneous pavement section. A common problem in modeling event duration is caused by unobserved failure events in a typical data set. Data collection surveys are usually of limited length. Thus, some pavement sections will have already failed by the day the survey starts, others will reach terminal conditions during the survey period, while others will only fail after the survey is concluded. If only the failure events observed during the survey are included in the statistical analysis (disregarding the information on the after and before events), the model developed will suffer from truncation bias If the censoring of the failure events is not accounted for properly, the model may suffer from censoring bias.

In this paper, an analysis of the data collected during the AASHO Road Test is presented. The analysis is based on the use of probabilistic duration modeling techniques. Duration models enable the stochastic nature of pavement failure time to be evaluated as well as censored data to be incorporated in the statistical estimation of the model parameters. The results, based on sound statistical principles, show that the failure times predicted with the model match the observed pavement failure data better than the original AASHO equation.

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1. Introduction

Predicting the actual performance of a specific pavement section under the combined action of highway traffic and environmental conditions provides valuable information to the highway agency for proper planning of maintenance and rehabilitation activities, budget estimation and allocation of resources. Pavement failure is a highly variable event which not only depends on layer material properties, environmental and subgrade condition and traffic loading, but also on the specific definition of failure adopted by the highway agency. Failure is usually defined in terms of amount of cracking, rut depth, surface roughness, skid resistance, or combinations of these or other indicators of performance Two types of pavement performance are of interested to the pavement engineer·

(i) Functional performance a subjective measure of the quality of the riding condition of the road from the users' point of view, e.g. serviceability, riding quality, etc.

(ii) Structural performance a more objective measure which takes into account the appearance of various forms of distress such as cracking, rutting, raveling, faulting, etc.

Observation of in-service pavements, accelerated pavement tests (APT), and laboratory and desk studies are used to evaluate pavement response and performance and to establish failure models for pavement life predictions. The best among these models have incorporated some kind of mechanistic-empirical considerations of the failure process. Although these mechanistic-empirical approaches include some stochastic considerations of material properties, environmental conditions and/or traffic loading, their predictions are in general deterministic (point predictions) and therefore, unrealistic.

The first full scale APT experiments were conducted in the United States in the late 1950s and they consisted of specially built sections subjected to actual traffic loading. Three such tests deserve special mention because of the influence they exerted on pavement design: The

Maryland Test, The WASHO Test and, the most important, the AASHO Road Test.

The objective of this study was to develop performance models to predict pavement failure time based on the data collected from accelerated pavement testing facilities such as the AASHO Road Test (HRB, 1960). These data are commonly known as experimental pavement failure data, to differentiate them from in-service pavement data, such as the FHWA Long Term Pavement Performance (LTPP) data. Paterson and Chesher (1986) have applied the same method to in-service data as part of the development of the HDM III model (Paterson 1987).

2. Background

2.1 The AASHO Road Test

The AASHO Road Test took place in the late 50s and was located near Ottawa (IL) The site was chosen because the soil in the area was uniform and representative of soils in large areas of the country. The climate was also considered to be representative of many states in the northern United States (HRB, 1960). Hence, only one subgrade material was evaluated during the experiment as well as only one climatic region. Even though both condition are typical of large areas of the United States, the use of the results outside these conditions should be subjected to detailed assessment of their applicability. Besides, estimation of the effects of other subgrade material and/or environmental conditions cannot be attained with this data set

The test tracks consisted of four large loops, numbered 3 through 6, and two small loops, numbered 1 and 2 Each loop was a segment of a four-lane divided highway whose north tangents were surfaced with asphalt concrete (AC) and the south tangents with Portland cement concrete (PCC) Only loops 2 through 6 were subjected to traffic, all vehicles assigned to any one traffic lane had the same axle arrangement-axle load configuration. Table 1 shows a summary of the traffic loading configuration applied to each loop and lane. Whenever possible, the traffic was operated at 35 mph on the test tangents. A total of approximately 1,114,000 axle load repetitions were applied from November 1958 until December 1960.

Table 1: axle arrangement and axle load configurations

Loop	Lane	Axle configuration	Weight in kips		
			Front axle	Load axle	Gross weight
2	1	1-1	2	2	4
2	2	1-1	2	6	8
3	1	1-1-1	4	12	28
3	2	1-2-2	6	24	54
4	1	1-1-1	6	18	42
4	2	1-2-2	9	32	73
5	1	1-1-1	6	22 4	51
5	2	1-2-2	9	40	89
6	1	1-1-1	9	30	69
6	2	1-2-2	12	48	108

Most of the sections on the flexible pavement tangents were part of a complete experimental design, the design factors of which were surface thickness, base thickness and subbase thickness The dimensions of the main factorial designs were 3x3x3, that is, three levels of surface thickness combined with three different base thicknesses and three subbase thicknesses.

The material used for the construction of the AC surface, base and subbase layers were kept the same for all sections, hence, the effect of the material properties on pavement performance cannot be assessed form the data of the main experimental design. Other experiments aimed at assessing different surface and base materials were also conducted during the AASHO Road Test but were not part of the main experimental design and therefore, were not considered in the development of the models presented in this paper

2.2 Regression models

The initial attempts at developing performance models made use of regression to develop pavement damage functions. Damage functions are mathematical equations aimed at predicting a specific distress, response or reduction in functional performance as a function of traffic loading or time The first form of such function was developed based on the analysis of the data of the AASHO Road Test. The form of the damage function was the following

$$g_t = \left(\frac{ESA_t}{\rho} \right)^{\beta} \tag{1}$$

where g_t : damage at time t,

ESA_t number of equivalent standard 18 kips axle loads applied up to time t,

ρ ESA required to produce a damage level defined as failure, and

β . power that represents the rate of damage increase.

The parameters ρ and β (estimated by regression analysis) differ with the type of distress and are functions of a variety of explanatory variables consistent with the form of performance under consideration. In the AASHO design equation, the damage function is defined in terms of the serviceability index ratio:

$$g_t = \frac{p_o - p_t}{p_o - p_f} \tag{2}$$

Where p_o and p_f are the initial and terminal conditions as measured by the present serviceability index (PSI), and p_t is the value of PSI at time t. Based on the above definition of damage, the form of the AASHO performance model was:

$$p_t = p_o - (p_o - p_f)\left(\frac{ESA_t}{\rho}\right)^{\beta} \tag{3}$$

The damage function given in Equation (1) resulted from accelerated testing in one environment and essentially for one subgrade, so new damage functions applicable to other environments and subgrades were needed Research incorporating mechanistic principles and new experimental data (Rauhut et al, 1983) developed improved models for the prediction of the reduction in PSI, rut depth and fatigue cracking. These researchers developed models that could be applied to a wider range of conditions than those conditions prevailing during the AASHO Road Test.

Another improvement to the original AASHO Road Test performance model was due to the assumption that an S-shaped curve would predict more realistic long-term pavement performance (Garcia-Diaz and Riggins, 1984). That is, it was recognized that the pavement deterioration rate decreases towards the end of the pavement life. This behavior is typical of pavements that have received adequate routine maintenance in the past The same study also introduced the idea that pavement distress is better represented by two separate components· extent and degree.

A similar basic approach has been used recently (Sebaaly et al, 1995) to develop nine performance models for flexible pavement maintenance treatments The authors of this study concluded that the nine models developed have very good fit to data as measured by the coefficient of determination *(R^2)* of the regressions. It was also observed that the sign of the variables' coefficients were sometimes opposite to engineering judgment This situation was attributed to the presence of outliers within the data set, without further analysis of the possible statistical significance of these outliers. However, it is also possible that some fundamental errors were committed during the statistical analysis of the data. Because each data set consisted of pavement sections which received a specific treatment, and because the treatments were not assigned randomly by the highway agency, it is likely that these data were selected and that the resulting models suffered from selectivity bias (Madanat and Mishalani, 1998)

Other authors have established that AASHO's functional specification and statistical estimation of the coefficients in the deterioration model were seriously flawed due to inappropriate treatment of censored observations (Paterson, 1987; Small and Winston, 1988) and proposed new estimates based on Tobit analysis (Small and Winston, 1988) The latter study also established that the original AASHO models overestimate the life of thicker pavements (those with large structural number) and concluded that this is a possible reason for higher traffic highways not performing as expected It should also be recognized that prediction of the estimated life for thick pavements (based on the AASHO Road Test data) involves extrapolation well beyond the range of direct observation (Recall that during the AASHO Road Test just over a million axle load repetitions were applied) Although several researchers have proposed improvements to the original AASHO equation, these improvements never enjoyed the widespread applicability that the original equation did

2.3 Duration models

The initiation of pavement distress is a highly variable event, that is, distress occurs at different times at various locations along a homogeneous piece of road Hence, the time of failure should be represented by a probability density function rather than by a point estimate Because data collection surveys are in many cases of limited duration, in addition to the considerable variability in failure times, there is the difficulty of unobserved failure events in a typical set of pavement condition data (Paterson, 1987). Often, only the distress events observed during the survey are included in the statistical analysis Therefore, important information about the stochastic and mechanistic properties coming from the before and after events are excluded causing a bias in the model. These excluded events are known as censored data (Greene, 1993). Both the stochastic variations and the censoring of the dependent variable can be addressed by using an estimation procedure based on the principles of failure-time analysis (Kalbfleisch and Prentice, 1980, Paterson and Chesher, 1986, Paterson et al, 1989). The procedure makes use of.

(i) the statistical method of maximum likelihood estimation to take into account both censored and uncensored data (as described in Section 3.2), and

(ii) a distribution that enables the variability of failure times to be estimated from the data. As explained further in Section 3 3, a Weibull distribution was selected for this purpose because it was considered to be representative of the failure process.

Due to the randomness of pavement failure and the fact that information is usually available over a limited period, duration models accounting for censored data seem to be a sound approach to deterioration modeling. This is specially the case when experimental pavement data are used, because such data sets consist of continuous observations of pavement performance, allowing the analyst to obtain precise measurements of failure times

3. Modeling approach

3.1 General

Terminal pavement conditions will be reached at different times at various locations along a homogeneous road. If we refer to this time as τ, we can consider τ as a random variable with a given density $f(\tau)$ In general, pavement engineers are interested in the probability that the pavement will not have failed by a certain age t, this is represented by a survival function $S(\tau=t) = S(t)$ By definition, $S(t) = Pr(\tau > t) = 1 - F(t)$, where $F(t)$ is the cumulative distribution function of τ

As indicated earlier, data collection surveys are usually of limited length and, in general, they do not start at the beginning of the pavement life. That is, for a given data set, some pavement sections will have already failed by the day the survey starts, others will reach terminal conditions during the survey period, while others will only fail after the survey is concluded.

If only the failure events observed during the survey were included in the statistical analysis (disregarding the censored information on the after and before events) the model developed would suffer from truncation bias. If the censoring of the failure events is not accounted for properly, then the model may suffer from censoring bias. The information on the *after* events is of particular importance in representing the stronger, long-life pavement sections; while the information of the *before* events reflects the performance of the lighter pavement structures By using probabilistic duration techniques, both the stochastic variation of failure times and the potentiality of censored data are incorporated in the development of the model (Kalbfleisch and Prentice, 1980, Paterson and Chesher, 1986, Paterson et al, 1989)

3.2 Censored data

To give the analysis general applicability, the random variable τ will be defined as the time from initial construction of the pavement section until a preset terminal condition level is reached If the collection data survey extends from $\tau = t_0$ years after construction (or rehabilitation) until $\tau = t_f$, then the following conditions are mutually exclusive·

(i) $\tau \leq t_0$, the pavement has failed prior to the initiation of the data collection survey. In this case, we define $D_1 = 1$, otherwise $D_1 = 0$

(ii) $t_0 < \tau \leq t_f$, this condition implies that failure has occurred during the observation period In this case we define $D_2 = 1$, otherwise $D_2 = 0$. We also define t as the observed value of τ

(iii) $t_f < \tau$, failure has not occurred by the time the data collection survey concluded. In this case we define $D_3 = 1$, otherwise $D_3 = 0$.

Under conditions (i) and (iii) above the actual failure time is unknown so a new random variable T is defined such that:

$$T = t_0 \text{ if } D_1 = 1$$

$$T = t \text{ if } D_2 = 1, \text{ and}$$

$$T = t_f \text{ if } D_3 = 1$$

By taking a sample of pavement sections values for D_1, D_2, D_3 and T are obtained and then, the joint probability is considered in order to develop a maximum likelihood estimator. The joint probability consists of the product of the probability mass function of the discrete variables D_1, D_2 and D_3 and the probability density function of the continuous variable T.

The discrete variables D_1, D_2 and D_3 have a multinomial distribution with the following probability mass function:

$$P(D_1 = 1) = F(t_0),$$

$$P(D_2 = 1) = F(t_f) - F(t_0), \text{ and}$$

$$P(D_3 = 1) = 1 - F(t_f) = S(t_f)$$

Conditional on $D_1 = 1$ or $D_3 = 1$, t is respectively t_0 or t_f with probability one in each case Conditional on $D_2 = 1$, t has the following truncated probability density function given by:

$$f(t | t_o < t < t_f) = \frac{f(t)}{F(t_f) - F(t_o)} \quad (4)$$

Multiplying marginal and conditional probabilities the joint probability for each section is obtained as follows:

$$P(D_1 \cap D_2 \cap D_3 \cap t) = F(t)^{D_1} f(t)^{D_2} S(t)^{D_3} \tag{5}$$

The pavement failure model can be developed by expressing the conditional failure time in terms of exogenous variables $\underline{X}$ (such as traffic and pavement characteristics) and parameters $\underline{\theta}$ as follows:

$$P(D_1 \cap D_2 \cap D_3 \cap t|\underline{X},\underline{\theta}) = F(t|\underline{X},\underline{\theta})^{D_1} f(t|\underline{X},\underline{\theta})^{D_2} S(t|\underline{X},\underline{\theta})^{D_3} \tag{6}$$

The estimation of $\underline{\theta}$ can be achieved by using maximum likelihood estimation. The maximum likelihood estimator of $\underline{\theta}$ is the value of $\underline{\theta}$ which maximizes the likelihood function. i.e , the product of the joint probabilities of the n observations in the sample:

$$L(\underline{\theta}) = P(D_1, D_2 ..., D_n; t_1, t_2 . . t_n|\underline{X},\underline{\theta}) = \prod_{i=1}^{n} F(t_i|\underline{X}_i,\underline{\theta})^{D_{1i}} f(t_i|\underline{X}_i,\underline{\theta})^{D_{2i}} S(t_i|\underline{X}_i,\underline{\theta})^{D_{3i}} \tag{7}$$

Equivalently, the log-likelihood function can be maximized·

$$\ln L(\underline{\theta}) = \sum_{i=1}^{n} \{D_{1i} \log F(t_i|\underline{X}_i,\underline{\theta}) + D_{2i} \log f(t_i|\underline{X}_i,\underline{\theta}) + D_{3i} \log S(t_i|\underline{X}_i,\underline{\theta})\} \tag{8}$$

$\hat{\underline{\theta}}$ is obtained using numerical methods Under general conditions $\hat{\underline{\theta}}$ is consistent and efficient.

3 3 Variability of failure time

The time to failure of a given pavement section depends also on the definition of failure used. In the AASHO road test, a pavement section was considered to have failed when its present serviceability index reached a value of 1 5. Our discussion of failure is given in this context.

The hazard rate function $\lambda(t)$, a concept used in reliability theory, is proportional to the probability that failure will occur in a short time interval given that it has not occurred previously. It is defined as:

$$\lambda(t) = \frac{f(t)}{1-F(t)} = \frac{f(t)}{S(t)} = -\frac{d \ln S(t)}{dt} \tag{9}$$

Hence, the hazard rate is the rate at which failure will occur after a time t, given that it has not happened yet at time t. For our purposes it may be preferable to model the hazard function rather than the density function, the cumulative density function. or the survival function In any case, all four are related as indicated in the previous equation. Another useful equation for working with the hazard function is the integrated hazard function.

$$\Lambda(t) = \int^{t} \lambda(t)dt, \qquad hence \qquad S(t) = e^{-\Lambda(t)} \tag{10}$$

Modeling hazard rate

As indicated previously, it seems more appealing to model the hazard function directly and then, for estimation purposes, differentiate to obtain the density. For instance, in the case of pavements, it could be argued that the hazard function is increasing or decreasing. However, it is more likely that the hazard function increases, i.e. that the rate at which failure occurs increases with pavement age

Therefore, a variable rate hazard function that results in a Weibull distribution was used in this study In this case, the rate can either increase or decrease depending on the value of the parameter p, $(p \neq 1)$ that is estimated from the data. The Weibull hazard function is given by.

$$\lambda(t) = \lambda p(\lambda t)^{p-1}, \qquad hence \qquad S(t) = e^{-(\lambda t)^p} \tag{11}$$

The parameters $\underline{\theta} = (\lambda, p)$ of this model can be estimated by maximum likelihood. Assuming that the data set does not include left-censored observations, the log-likelihood function is:

$$\ln L(\underline{\theta}) = \sum_i D_{2i} \ln f(t_i|\underline{\theta}) + \sum_i D_{3i} \ln S(t_i|\underline{\theta}) \tag{12}$$

Exogenous Variables

The parametric model described above can be extended to account for the effect of exogenous factors in shaping the survival distribution. In the case of the prediction of pavement failure time, the extension of the Weibull model will be considered:

$$\lambda_i = e^{-\underline{\theta}\underline{X}_i} \tag{13}$$

Where $\underline{\theta}$ is a vector of parameters, and $\underline{X}_i$ is a vector of exogenous variables for pavement section i which are assumed not to change from construction time $(T = 0)$ to the failure time $(T = t)$ Making λ a function of a set of exogenous variables is equivalent to changing the units of measurement on the time axis For this reason these models are sometimes called "accelerated failure time" models The following transformation is used·

$$\sigma = \frac{1}{p} \qquad and \qquad w_i = p\ln(\lambda_i t_i) = \frac{\ln t_i - \underline{\theta}\underline{X}_i}{\sigma} \tag{14}$$

The density and survival functions in terms of w become:

$$f(w_i) = \left(\frac{1}{\sigma}\right)\exp(w_i - e^{w_i}) \tag{15}$$

$$S(w_i) = \exp(-e^{w_i}) \quad (16)$$

The log-likelihood function becomes:

$$\ln L(\underline{\theta}) = \sum_i [D_{2i} \ln f(w_i) + D_{3i} \ln S(w_i)] \quad (17)$$

The hazard function depends on t, p, and X The signs of the estimated coefficients suggest the direction of the effects of the variables on the hazard function when the hazard is monotonic In the case of the Weibull model, the expected duration is easily computed as:

$$E[t|\underline{X}_i] = \exp(p\underline{\theta}\underline{X}_i) \quad (18)$$

It should be noted that in the failure time models, the goodness of fit cannot be properly assessed by the coefficient of determination. Furthermore, because the model used is not a linear regression model, there is no obvious equivalent to the conventionally reported *standard error*. In order to assess the significance of the parameters, the Berndt, Hall, Hall and Hausman (BHHH) estimator or actual derivatives can be used to estimate asymptotic standard errors for the estimates (Paterson 1987).

4. Application

In Section 2, the form of the selected deterioration model developed during the analysis of the AASHO Road Test data was presented (Equations 1-3). During the original analysis of the AASHO data, it was proposed that the values of β (deterioration rate) and ρ (number of repetitions to failure) should be expressed as a function of pavement and traffic characteristics (HRB, 1960). The resulting equation for ρ was·

$$\rho = \frac{A_o (D+1)^{A_1} L_2^{A_3}}{(L_1 + L_2)^{A_2}} \tag{19}$$

where D	:	structural number of the pavement section,
L_1	:	axle load in kips,
L_2	:	dummy variable ($L_2=1$ for single axles, $L_2=2$ for tandem axles),
$A_o, .., A_3$	:	parameters

The data used for the estimation of the parameters of the above equation are given in the appendix to Report 5 of the AASHO Road Test (HRB, 1960). The parameters of the above equation were originally estimated using an ad-hoc stepwise regression procedure, and the following equation was developed (HRB, 1960):

$$\rho = \frac{10^{5.93} (D+1)^{9.36} L_2^{4.33}}{(L_1 + L_2)^{4.79}} \tag{20}$$

Further details of how the parameters of this equation were estimated are unclear in the literature. In particular, it is uncertain how the censored data were accounted for. Despite all its known flaws, this equation (or slight variations of it) has been the main tool for the design of bituminous roads in the U.S. and around the world for almost half a century It is also well known that a number of studies have reported great variations between the predictions of the above equations and the performance of actual pavements (Paterson, 1987; Small and Winston, 1988)

In the present study duration models were used to develop a counterpart to the above equation. In the context of the AASHO Road Test data, the observation period started with new pavement sections. Therefore, none of the pavement failures occurred prior to the observation period and thus the problem of left-censoring was not observed On the other hand, several sections had not reached failure at the end of the experiment (approximately 1,114,000 axle repetitions). Thus, there are a number of *after* events, which are right-censored observations

An extension of the Weibull model was used, in which the hazard rate was a function of exogenous variables. These variables were the same regressors used in the AASHO model, namely D, L_1 and L_2. The details of the estimation are presented in Table 2 and Figures 1 and 2, which show the plots of the hazard and survival functions estimated in this study, respectively.

Table 2: Estimation Results

Variable	Estimated parameter	t -statistic
Constant	12.15	50.93
log(D+1)	6 68	37.03
$\log(L_2)$	2 62	12.30
$\log(L_1+L_2)$	-3 03	-23.47
σ	0.75	17.62

Dependent variable. number of axle load repetitions to failure (ρ). Number of observations 284

Thus, by using duration models, the resulting equation is:

$$E[\rho] = \exp(12\ 15 + 6.68\ln(D+1) + 2\ 62\ln(L_2) - 3.03\ln(L_1 + L_2)) \tag{21}$$

Which, transformed into a similar form as the AASHO equation, results in the following expression:

$$E[\rho] = \frac{10^{5\ 28}(D+1)^{6\ 68} L_2^{\ 2\ 62}}{(L_1 + L_2)^{3\ 03}} \tag{22}$$

It can be seen that the parameter estimates ın equation (22) are smaller in magnıtude than the corresponding estimates in equation (20) It is also important to notıce the hıgh statistical significance of all the parameter estımated based on the t-statistıcs given in Table 2.

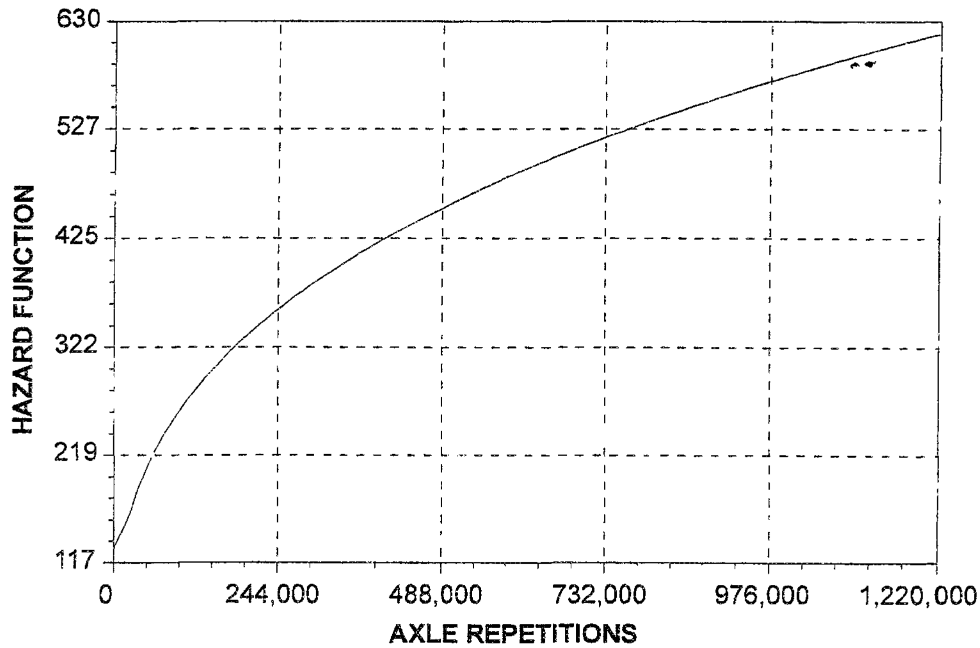

Figure 1: Hazard rate function.

The use of duration model enables the estımatıon of pavement lıfe as well as ıts probabılıty distribution. By using the dıstributıon of pavement lıfe instead of a poınt estımatıon, a reliable sensitivity analyses can be carried out in order to estımate the ımpacts of different maıntenance and rehabilıtatıon strategies, and the effects of dıfferent budgets on the condıtions of the road network.

Thus, from the engineer poınt of vıew is more relevant to know the probability that a gıven pavement section will faıl given that it has not failed to a gıven date. Thıs is gıven by the hazard function and is represented in Figure 1 The hazard function is used for assessing the reliability of the various pavement sections The estimated value for the parameter p of the Weibull model was 1.34 (i.e bigger that one) so the rate at which failure occurs is expected to increase with pavement age (Figure 1).

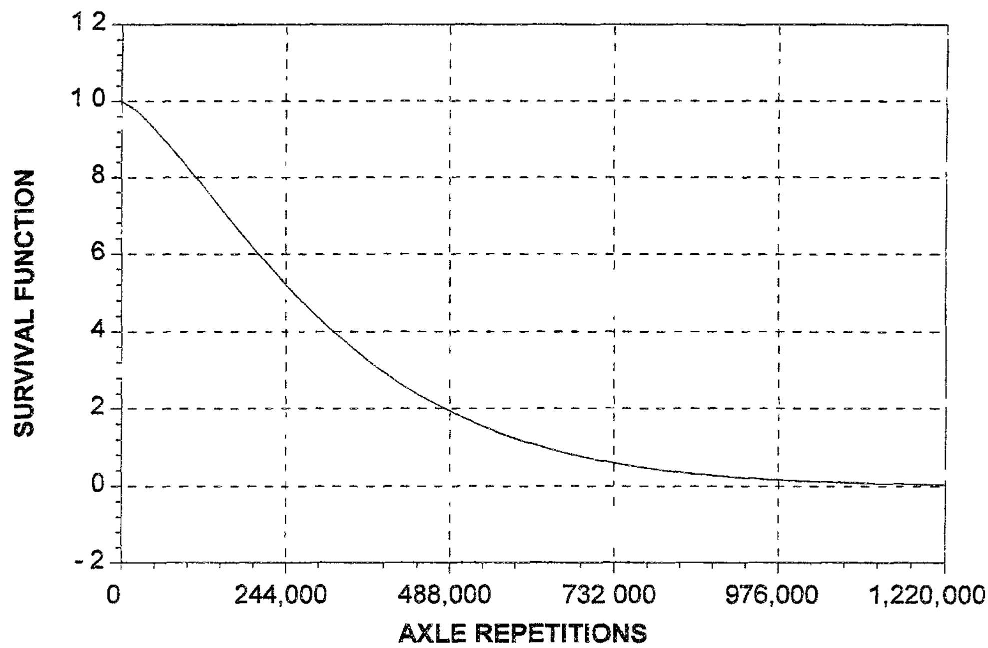

Figure 2: Survival function.

Other important information, which is directly available when using duration models, is the probability that the pavement will last longer that a given time T = t. This information is given by the survival function (Figure 2). Once the hazard and the survival function are known, the probability distribution can be determined by the product of the two, as indicated by Equation 9.

The predictions of pavement lives obtained by using this new equation match the observed lives better than those obtained by using the original AASHO equation (Figure 3) This can be objectively measured by the estimates of the standard errors of the two models, which are given by the square root of the average squared residuals. The standard error of the AASHO equation is 0.65 while the standard error for the duration model equation is 0 42 This represents a reduction in the standard error of the forecast of about 35 percent Thus, the new equation is not only statistically sound but also fits the data better than the original AASHO equation

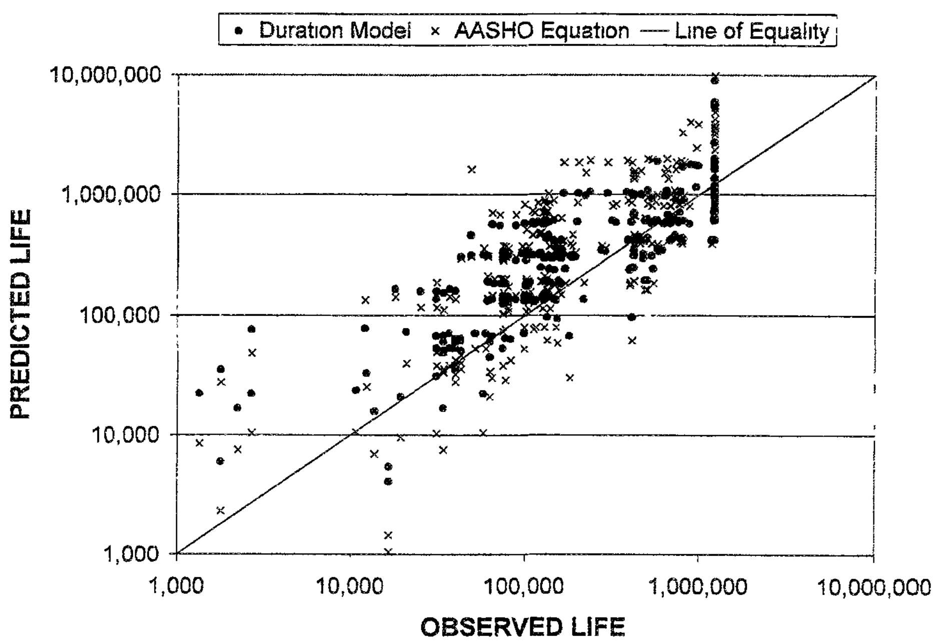

Figure 3: Observed versus predicted pavement performance.

An important aspect to be noted in Figure 3 is the fact that, in general, both equations (the original AASHO Equation and the new based on duration model techniques) seem to overestimate the performance of those pavements that had failed during the test That is, there are many more points above the equality line than below it

Figure 4 shows the performance of a random sample of 56 sections (20 percent of total); the section have been numbered in order of ascending observed pavement life. It can be seen that for light pavement structures, the duration model over-predicts more that the AASHO model. For those sections of average strength, both models prediction are similar. Finally, for heavier pavement structures, the AASHO model tends to over-predict pavement life while the duration model yields fairly good predictions.

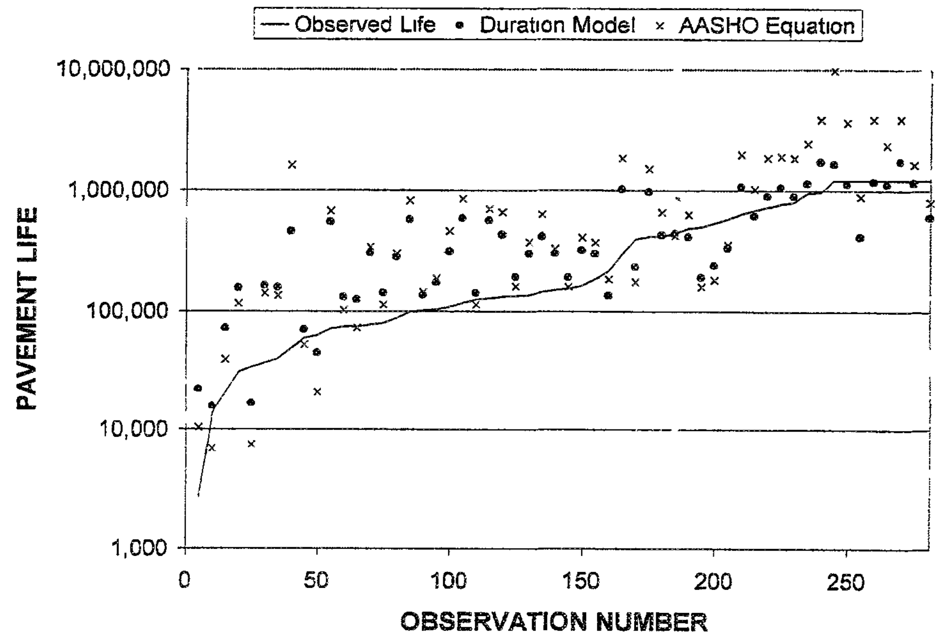

Figure 4: Comparative performance of both models.

By the end of the test, 237 out of 284 of the sections of the main experiments design had actually failed The original AASHO Equation predicted that 215 would fail, while the duration model predicted 253. That is, an error of -9 3 percent and +6.8 percent respectively.

The exponent of the variable $(L_1 + L_2)$ is of particular interest since it indicates the sensitivity of the pavement sections to overloading Hence, it is an indicator of the damage coefficient of the well-known power law. It should be noted that the new exponent is 36 percent lower that the original one. Because this exponent has a significant influence on the design of heavy traffic pavements, this difference is expected to have important economic consequences. This aspect, which has been observed for many researchers over the past 35 years, has never been paid the necessary attention. One the one hand, the effect of heavy loads on pavement damage is over-predicted but, on the other hand the effect of lighter loads is under-estimated.

The use of duration models enables a more comprehensive assessment of the stochastic nature of failure time. Not only the expected life of the road is determined, but also its probabilistic distribution The hazard rate function and the integrated hazard rate function are determined in the process too The survival function, which represents the probability that a given pavement will exceed a given life, is also obtained, thus providing valuable information to the pavement engineer in charge of managing the road network.

5. Discussion

In this study, an analysis of the data collected during the AASHO Road Test was conducted This analysis is based on the use of probabilistic duration modeling techniques Duration techniques enable the stochastic nature of pavement failure time to be evaluated as well as censored data to be incorporated in the statistical estimation of the model parameters Due to the nature of the road failure phenomenon, the presence of censored data is almost unavoidable and not accounting for such data would produce biased model parameters

The model developed in this paper has two main advantages over the original AASHO model. First, it is based on sound statistical principles, and therefore it is free of any subjective judgment. Second, the failure times predicted with the newly developed model match the data better than the original equation; as the results show, there was a reduction of about 35 percent in the standard error of the forecast

The estimate of the coefficient of the axle load obtained in this study is significantly lower than the estimate obtained by the AASHO researchers. This finding indicates that the exponent of the power law used by pavement engineers in the computation of load equivalency factors may be overestimated Further analysis of the data should be conducted to verify this finding.

Prediction of facility performance is a critical component of the pavement management process at both the project and network levels Previous research has demonstrated the cost-benefit of accurate prediction of pavement deterioration (Madanat 1993). In a set of simulation experiments, the minimum expected life-cycle costs of a pavement section were found to increase rapidly with the standard error of the deterioration model forecast. This paper has shown that probabilistic duration modeling methods have the potential to improve the accuracy of pavement deterioration prediction. Using such models in the context of pavement management should therefore lead to important lifecycle cost savings.

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