# EFFECT OF ENVIRONMENTAL FACTORS ON PAVEMENT DETERIORATION

## FINAL REPORT
## Volume I of II
## Background and Methodology

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16. Abstract

A computerized model for the determination of pavement deterioration responsibilities due to load and non-load related factors was developed. The model is based on predicted pavement performance and the relationship of pavement field performance to a quantification of level of routine maintenance. Predicted performance provides the basis to quantify total pavement deterioration due to load-related factors. Field performance measurements and a quantification of level of routine maintenance are used to quantify total pavement deterioration due to load and non-load related factors. Proportionality assumptions are made to determine pavement deterioration responsibilities based on these relationships. Volume I describes the Performance Based Approach, the theoretical basis for the model, and the methodology applied to create the computer model. Volume II presents the Software User's Manual and the BASIC source code of the computer model.

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# Abstract

A computerized model for the determination of pavement deterioration responsibilities due to load and non-load related factors was developed. The model is based on a relationship of pavement performances, as predicted by pavement structure design equations and as measured in the field, and a quantification of level of routine maintenance. Predicted pavement performance provides the basis to quantify total pavement deterioration due to load-related factors. Field performance measurements and a quantification of level of routine maintenance are used to quantify total pavement deterioration due to both load and non-load related factors. Proportionality assumptions are made to determine pavement deterioration responsibilities based on these quantities. Finally, an introduction to the computer model is presented.

## Disclaimer

## Notice

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## 1. Introduction

Pavement performance is affected by load-related and non-load related factors (i.e. traffic and environment, respectively). The determination of responsibility of each, that is, the percentage of the total deterioration, is of concern to transportation economists and engineers. For economists, the separation of traffic-related and environmental-related pavement deterioration is applied during highway cost allocation studies. Hence, it is necessary to determine the cost of pavement maintenance* due to pavement deterioration generated by traffic and its fair distribution among the different users. For engineers, this separation can be used to improve pavement design procedures.

The Oregon Department of Transportation (ODOT) has a need to determine the proportion of pavement deterioration which is related to environmental (non-load related) factors. A study conducted in 1980 resulted in a 10 percent portion of pavement distress assigned to non-load-related factors (Merris, 1986). This was based on the judgement of Highway Division maintenance and research engineers.

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* The results of this study will be used to allocate maintenance costs only. Cost allocation for original construction is handled separately through an incremental approach.

The study reported herein identifies a quantitative approach to assign pavement distress responsibility which is based on engineering theory of pavement design, field pavement performance data, and routine maintenance data. The method is implemented through a computer program, the development of which constitutes a major portion of the study.

Several methodologies have been used to estimate the level of responsibility that may be assigned to non-load-related factors, including: 1) Performance Based Approach, 2) Structured Subjective Judgement of Experienced Personnel (e.g. Utility Theory), 3) Distress Modeling, and 4) Bayesian Approach. During the preliminary stage of this study, two methodologies were proposed for the creation of the responsibility model, these being the Performance Based Approach and the Utility Theory. The Performance Based Approach as originally developed by Fwa and Sinha (1984) was selected for the final model because it applies concepts already used by ODOT, reduces subjective estimation, uses less data that are also more readily available, and is believed to be more acceptable to the user. Although not the recommended approach, Utility Theory is presented in appendix A because it may have value in comparing observed pavement condition to the results of the Performance Based Approach.

The Performance Based Approach uses theoretical and field pavement performance curves, and a quantification of pavement

maintenance history to determine deterioration responsibilities. Four proportions of deterioration responsibility representing load and non-load related factors, and their share in the interaction effects, are computed based on the areas bounded by the above mentioned curves, and an initial serviceability curve representing an ideal pavement for which no deterioration occurs during its service life. Although a more reliable methodology, the validity of the Performance Based Approach depends on the following assumptions:

- A measure of pavement performance (Pavement Condition Rating or Present Serviceability Index) which is commonly used, can be accurately predicted from equations, such as the AASHTO equation, when the traffic loading (ESALs) is known.
- The prediction equation used considers load-related factors only.
- The proportionality assumptions made to compute the different deterioration responsibilities are valid (see Section 3.5).
- A variable used to quantify the level of routine maintenance can be established.

Utility Theory is simply a structured method for organizing and using experienced judgement. It is a conceptual model of decision making (Raiffa, 1986), which in its simplest form consists of a set of alternative procedures to solve a problem

(e.g. relations of measures and degree of pavement distress with either pavement loading under traffic or environmental factors), a set of parameters which define and are common to the procedures (e.g. factors affecting pavement deterioration), and a set of possible outcomes which would result from applying the procedures to the problem (e.g. expected utility cost allocations).

Given an alternative procedure, the set of parameters, and a possible outcome, the decision maker, by applying Utility Theory, subjectively assigns values to each parameter. These values represent the share of responsibility of each parameter on the possible outcome. The combination of the values assigned to each parameter will yield the overall expected utility value for the alternative procedure. The best procedure to solve the problem will be the one with the highest expected utility value. Utility Theory was not selected as the methodology to be used in this project because it is a subjective evaluation and involves a complex procedure.

## 2. Survey of Methodologies

During the preliminary stages of work on the project, a survey was conducted of those methods being used by other state Highway Departments and of the pavement deterioration level allocated to environment. The information from this survey is summarized in Table 1.

Table 1: Survey of Methodologies Used by State Highway Departments to Measure the Effects of Environmental Factors on Pavement Deterioration.

| State | Study | Proportion of distress due to environment |
|---|---|---|
| Alaska | Correlation between climate and thermal cracking. | NA |
| California | Environmental effects measured using data from Maintenance Management System. | 30% *<br>22% ** |
| Hawaii | No study | NA |
| Montana | No study | NA |
| Nevada | No study | 25% |
| North Dakota | No study | NA |
| Oregon | No study | 10% |
| South Dakota | No study | NA |
| Texas | Damage due to swelling clays. | NA |
| Washington | Partial Mechanistic Approach | NA |
| Wyoming | No study | NA |

* environmental factor for pavement rehabilitation costs
** environmental factor for pavement maintenance costs
NA = No Assessment

The main results of the literature review and the survey, were the identification of those methodologies used for evaluating pavement performance, these being:

- Disaggregate Approach

- Aggregate Approach

and, of the methods used for the determination of deterioration responsibility, these being:

- Distress Modeling
- Subjective Judgement
- Performance Based Approach

The Disaggregate Approach involves breaking the problem down into components to mathematically model individual pavement distress types. The model predicts the amount and extent of the distress type in the pavement structure. In a broad sense, the development of these models involves first, the classification of those factors significant to pavement performance (e.g. Pavement Characteristics, Traffic Loading, and Environmental and Climatic Conditions). Next, a large amount of data is collected for each of the factors, and used as input for the creation of the models. Mathematical models are developed for each of the distress types being considered, and used to predict the expected level of distress. As applied to pavement deterioration responsibility analysis, through the Distress Modeling method, these levels are correlated to deterioration responsibility by using weighting factors which represent the responsibility of each vehicle class for each distress level.

The Aggregate Approach considers the gross performance of a pavement structure by means of a total measure of distress. This measure is predicted from equations, empirically developed, which are a function of traffic loading (ESALs) and pavement structure. As applied to pavement deterioration responsibility analysis, the performance predicted by the equations is compared to that measured on the field. By relating the measured value to the predicted value through proportionality assumptions the responsibilities can be estimated.

From the above descriptions, the main differences between the two approaches are: 1) Data; for the disaggregate approach the amount of data is large, and requires a greater handling effort than that of the aggregate approach. 2) Pavement Distress Analysis; the analysis done when using the disaggregate approach is more complex; further, given the limited current knowledge on the relationships between pavement performance and pavement distress, it is unreliable (Fwa and Sinha, 1984). Based on this, the aggregate approach was chosen as the way to predict pavement condition for the purpose of this study.

Subjective judgement refers to evaluating deterioration responsibilities based on the judgement of experienced personnel. Recently, transportation engineering researchers have applied Utility Theory to develop quantitative models of qualitative engineering problems. As applied to pavement deterioration

responsibility, Utility Theory would be a structured method for organizing and using experienced judgment of highway engineers.

The method developed in this study closely follows the Performance Based Approach, as developed by Fwa and Sinha (1984). This method compares field pavement performance to predicted pavement performance. The change in pavement condition from an ideal state to a state resulting from lack of routine maintenance during its service life, represents the total pavement deterioration due to load and non-load related factors and their interactions. The change in pavement condition from the ideal state to that state predicted by pavement structure design equations, would represent the deterioration due only to load-related factors. The ratio of the later state to the former state will represent the deterioration responsibility of load-related factors. The responsibility of the interaction effects and of the non-load-related factors is computed from equations developed on the basis of proportionality assumptions (see Sections 3.1 through 3.5.)

## 3. Performance Based Approach

### 3.1 Concepts

The Performance Based Approach is rooted in theories commonly used in transportation engineering. The concepts used and their application to the determination of deterioration responsibilities are briefly discussed in this section.

#### 3.1.1 Pavement Performance

The effects of load and non-load related factors acting on a pavement structure are deformation, stress, strain, fracture, polishing, and wear. The result of these effects reaching limiting values is the beginning of pavement distress. The type and extent of distress is known as pavement condition, and the measure of the present pavement condition is defined as serviceability (Hass and Hudson, 1982).

Serviceability is evaluated through different scales depending on the user. A well known technique was developed during the AASHO Road Test by Carey and Irick, and was termed the Present Serviceability Index (PSI) (Hass and Hudson, 1982). This index measures the serviceability of a pavement structure based on pavement roughness measurements. Another technique is the Riding Comfort Index (RCI) which evaluates pavement condition based on pavement riding quality. ODOT uses a Pavement Condition Rating (PCR) system based on subjective evaluations of distress made by

experienced personnel (ODOT, 1987).

The concept of Pavement Performance, as developed by Carey and Irick, refers to the evaluation or measurement of pavement serviceability with age or traffic, as shown in Figure 1 (Hass and Hudson, 1982). The initial level of serviceability reflects the condition of the pavement as constructed. As applied to the determination of deterioration responsibility, the performance concept is used to quantify pavement deterioration; hence, referring to Figure 2, the difference between the initial level of serviceability and the serviceability at time or traffic "t", or the change in pavement condition, is a valid measure of pavement deterioration.

### 3.1.2 Serviceability-ESAL Index

Fwa and Sinha developed a measure of pavement deterioration for use in their research on distress responsibilities called the PSI-ESAL Loss after the serviceability and traffic measurements PSI and ESALs (Equivalent Single Axle Load), respectively. For the purpose of the study presented herein, this measure was renamed Serviceability-ESAL Index (SEI) in order to cover a broader range of serviceability scales.

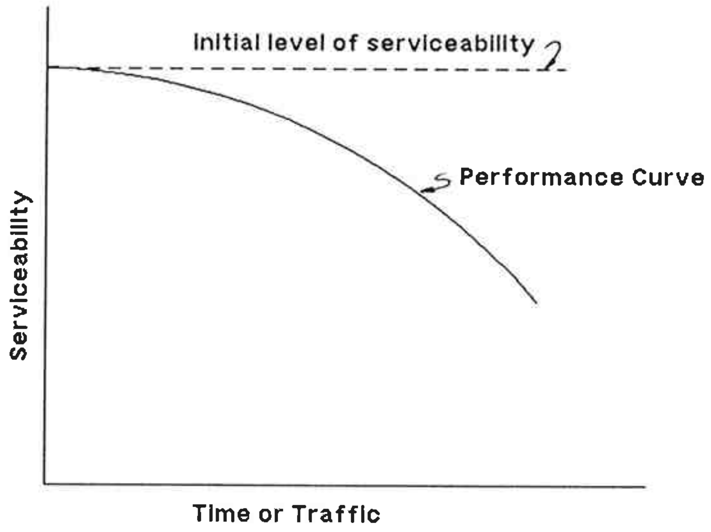


Figure 1: Evaluation of Pavement Serviceability with Time or Traffic : Performance

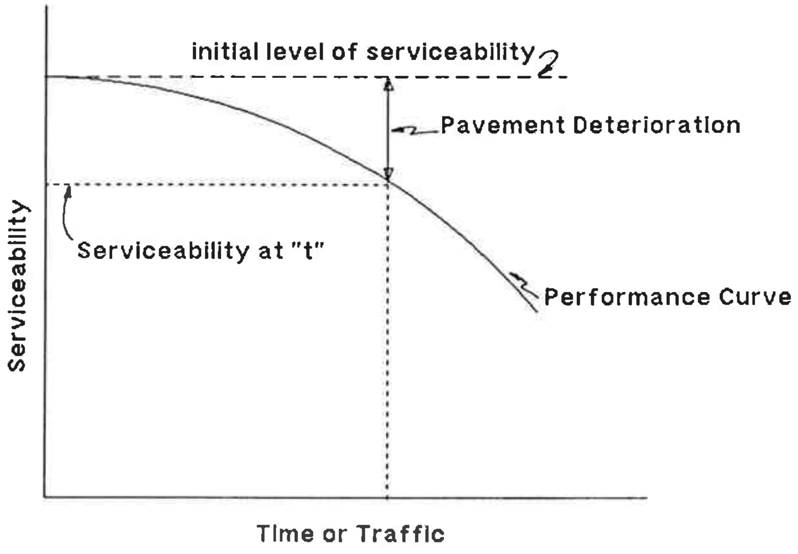


Figure 2: Pavement Deterioration as Quantified in the Performance Based Approach (after Fwa and Sinha).

As used in pavement deterioration responsibility analysis, SEI is represented by the hatched area in Figure 3. This index is interpreted as a cumulative measure of pavement deterioration through the service life of the pavement structure. Contrast this index with the measure of pavement deterioration as illustrated in Figure 2, which measures deterioration only at a specific point during the service life of the pavement structure. Since SEI (Figure 3) is represented by an area in the graph, it is a better representation of the gross amount of pavement deterioration. The application of this concept to pavement deterioration analysis will become clearer when it is used in the following sections.

### 3.1.3 Performance Curve for a Zero Level of Routine Maintenance

If no routine maintenance activities are carried out on the pavement structure during its life cycle, then the performance curve would represent the total change in pavement condition, or total deterioration, of the pavement structure due to load and non-load related factors and their interaction effects. This curve was named the zero level of routine maintenance performance curve by Fwa and Sinha.

Since routine maintenance is part of every highway department's annual maintenance activities, the actual field performance curve is between the zero level of routine maintenance and initial level of serviceability curves, as shown in Figure 4.

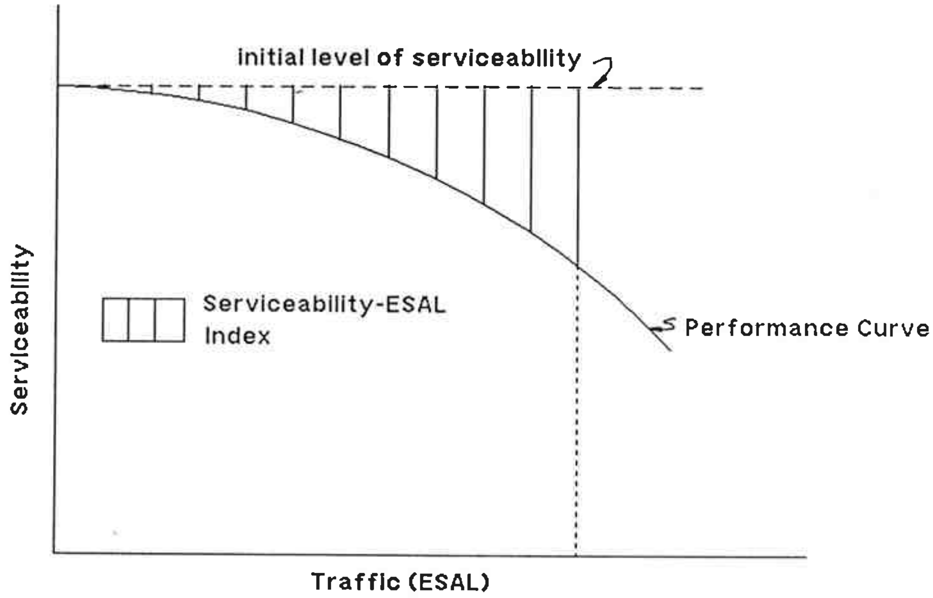


Figure 3: The Serviceability-ESAL Index Concept.
(after Fwa and Sinha)

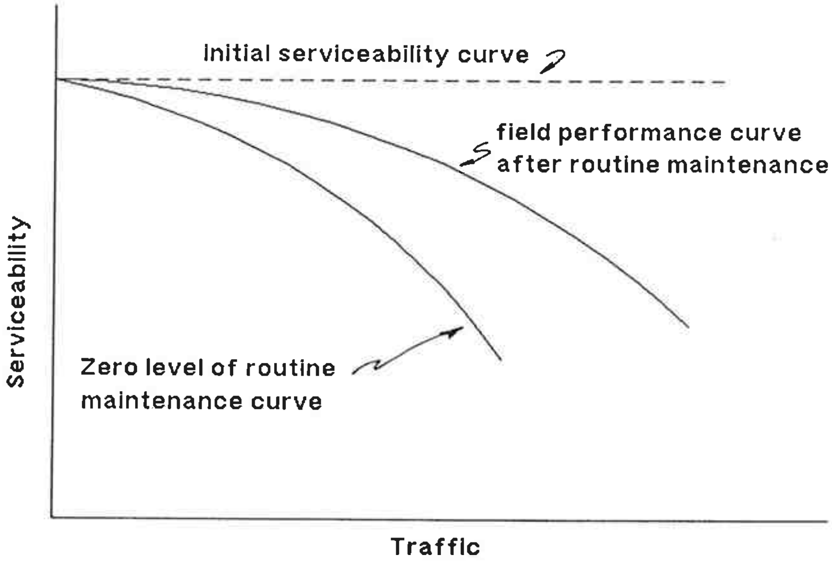


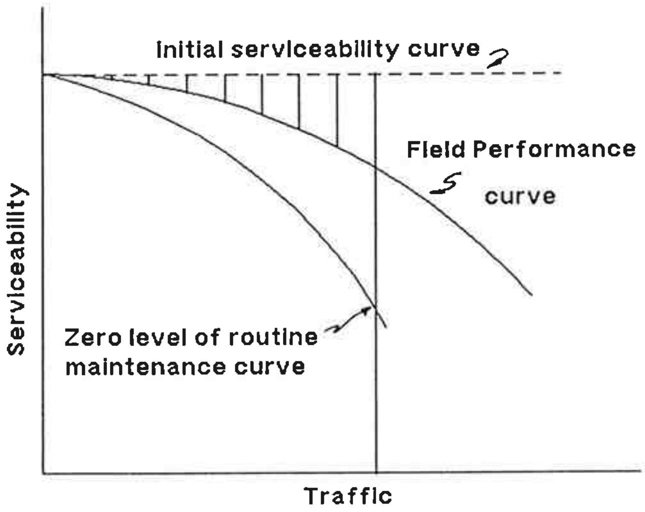
Figure 4: Effect of Routine Maintenance in Pavement Performance (after Fwa and Sinha).

This repositioning of the field performance curve reduces the amount of pavement deterioration as defined by SEI, as shown in Figure 5a. Before routine maintenance, pavement deterioration is represented by the area bounded by the Zero Level of Routine Maintenance and the initial serviceability curves (Figure 5(b)). After maintenance, the deterioration becomes the area between the field performance and the initial serviceability curves (Figure 5(a)). The difference between the two areas represents the deterioration repaired by routine maintenance. Hence, the amount of deterioration estimated, based on the field performance curve (Figure 5(a)), will not be the true total deterioration in the pavement.

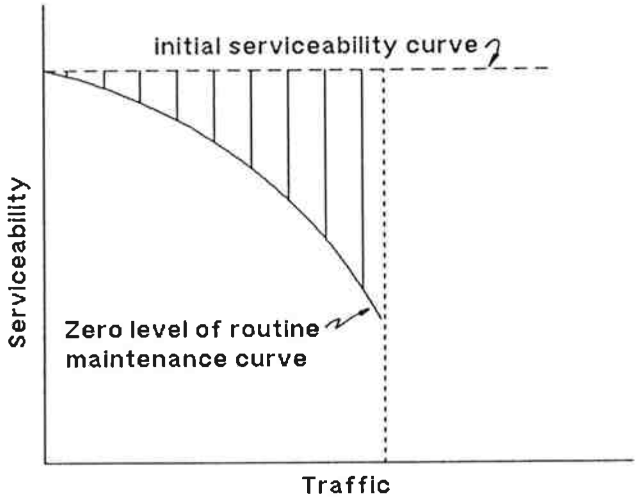
As applied to pavement deterioration responsibility analysis, a procedure to determine the total pavement deterioration (see Figure 5(b)) should be developed for a realistic estimate of responsibilities. This is discussed in Section 3.4 of this report.

### 3.1.4 Pavement Deterioration Proportions

As indicated in Section 3.1.1, pavement distress is caused by load and non-load related factors and their interaction effects acting on the pavement structure. To quantify this distress, the Serviceability-ESAL Index (SEI) was defined. The main purpose of this study is to develop software which will allow ODOT to compute the proportion of total pavement deterioration for each



a ) Pavement deterioration after routine maintenance



b ) Pavement Deterioration before routine maintenace

Figure 5: Effect of Routine Maintenance in Pavement Deterioration. (after Fwa and Sinha).

of the factors mentioned above. These proportions are shown schematically in Figure 6. As discussed in Section 3.1.3, the area bounded by the initial serviceability and zero level of routine maintenance curves, represents the cumulative total pavement deterioration during the life of the pavement structure, which equals the sum of the four different portions (A+B+C+D) shown in Figure 6.

Portion "A", represents the pavement deterioration due to purely load-related factors, assuming that the pavement structure design equation used considers these effects only. This area is bounded by the predicted performance curve and the initial serviceability curve. The predicted curve is defined by a performance equation (e.g. AASHTO Design Equation), as a function of traffic and other variables related to the pavement structure. In theory, this equation would predict the true performance of the pavement with time or traffic; the field performance curve is generally not the same, and it is usually plotted below the predicted curve as shown in Figure 7. The difference between the two curves indicates that pavement deterioration is caused by other factors in addition to load-related factors.

As applied to pavement deterioration responsibility analysis, it is assumed that area "A" on Figure 6, or area ☐ on Figure 7, represents the deterioration due to purely load-related factors,

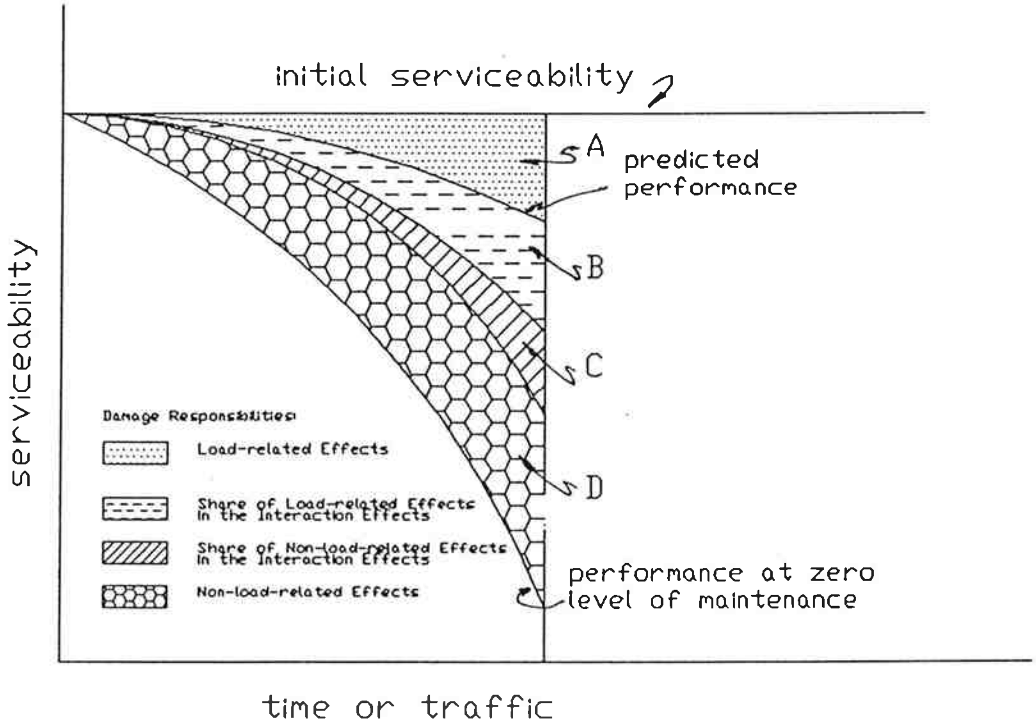


Figure 6: Schematic Representation of Deterioration Proportions.

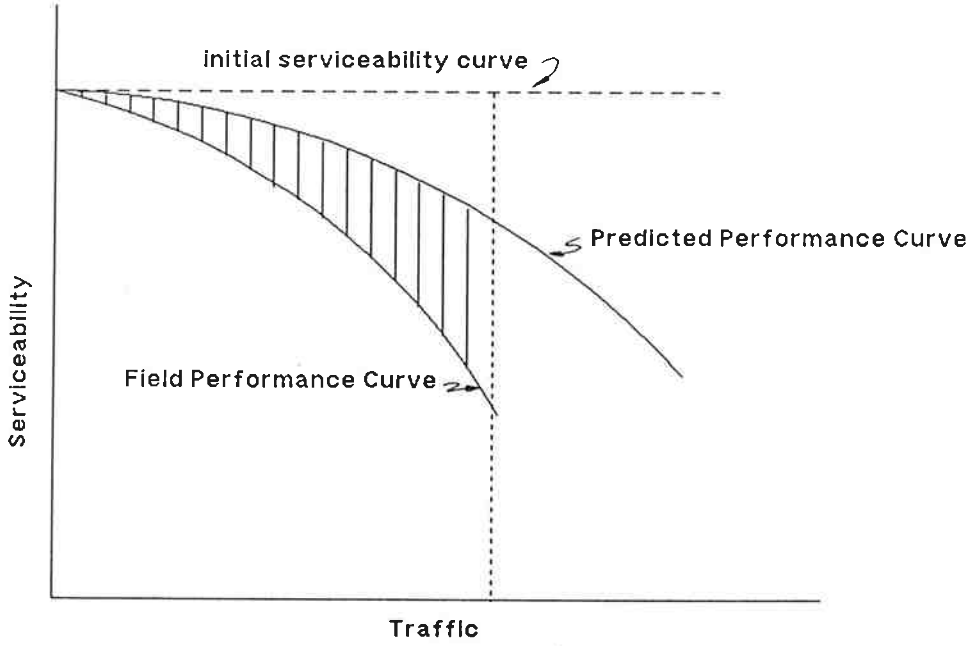


Figure 7: Schematic Representation of Pavement Deterioration Proportions.

and the area bounded by a zero-maintenance performance curve and the predicted performance curve, area "B+C+D" on Figure 6, represents the deterioration due to non-load-related factors and interaction effects. Portions "B" and "C" represent the share of load and non-load related factors in the interaction effects, respectively, and portion "D", the effect of purely non-load-related factors in the total pavement deterioration.

Referring to Section 3.1.2, routine maintenance reduces the true total amount of pavement deterioration. Therefore, area "B+C+D" on Figure 6 is not equal to area ▥ on Figure 7.

## 3.2 Methodology of Performance Based Approach

The purpose of this section is to link the concepts presented previously with the methodology of the Performance Based Approach. A flow chart of the approach is shown in Figure 8, each step of which will be discussed in general terms in this section.

The first information required in the Performance Based Approach is the deterioration responsibility due to purely load related factors. For this, it is required to select an equation which predicts pavement performance as a function of time or traffic and other structural variables. For example, Fwa and Sinha used the serviceability equation developed at the AASHO Road Test

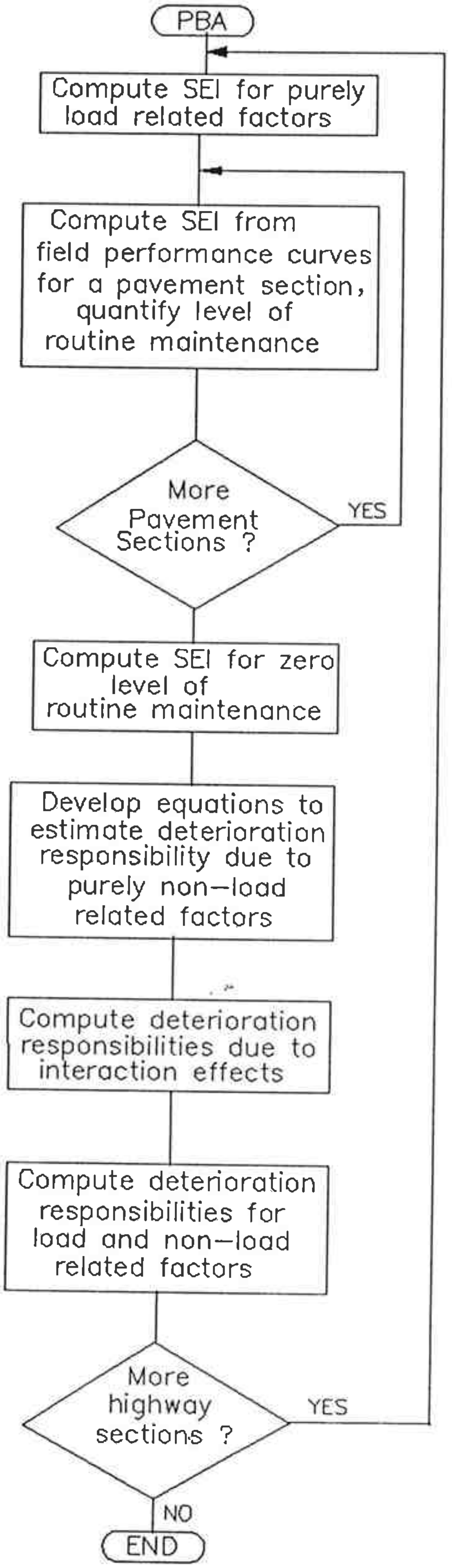


Figure 8: Flow Diagram for the Performance Based Approach Software

which expresses serviceability in terms of PSI, and is a function of traffic and pavement structural data (AASHTO, 1986). The application of the equation will generate the boundary curve of the area representing the portion of deterioration due to load-related factors, portion "A" of Figure 6. This portion will be mathematically related to the total pavement deterioration in order to compute the responsibility of load-related factors.

The computation of portion "A" is followed by the determination of that SEI value which represents the true total pavement deterioration, by using field performance curves and a quantification of the level of routine maintenance. For a highway section composed of various pavement sections which are structurally similar, and within the same climatic or environmental region, the SEI representing the true total pavement deterioration can be extrapolated from the SEI's and maintenance data of these pavement sections. This procedure is discussed in more detail in Section 3.4 of this report.

The determination of pavement deterioration responsibilities requires the development of equations which relate the two SEIs computed in the two steps above. The first equation is the ratio of the SEI representing the portion of deterioration due to load-related factors to the SEI representing the true total deterioration. This ratio is the percentage, or responsibility, of the total pavement deterioration caused by purely load-related

factors. For the other equations, proportionality assumptions are made between the factors and their shares in the interaction and total effects. The development of these equations is explained in Section 3.6.

From the proportionality assumptions, equations are developed that yield the responsibility of the non-load-related factors and the interaction effects. This is followed by the determination of the total responsibilities for load and non-load related factors.

## 3.3 Effects of Load Related Factors in Pavement Deterioration

### 3.3.1 Performance Models

Performance models have been developed to predict pavement performance as a function of different factors. For example, the AASHTO equation predicts performance as a function of traffic and pavement structural data (AASHTO, 1986). The Ontario Method of Performance Prediction uses subgrade deflection data to predict performance (Jung, Kher, and Phang, 1976).

In theory, the performance obtained from the models would represent the expected performance of the pavement in the field. However, observed or measured pavement performance is likely to be different from that given by prediction models. The error in the predicted values results mainly from the difficulty or

complexity encountered by researchers when they try to take into account environmental effects, interaction effects, degree of maintenance, quality of construction, etc., in the development of performance models. If it is assumed that the prediction models yield the change in performance caused by load-related factors, then the difference is interpreted as representing the change in performance due to non-load related factors and interaction effects.

For this study, it is assumed that the effects of load-related factors can be reliably estimated through performance models. This assumption makes it possible to compute the relative responsibility of these factors for reducing pavement performance. This may be achieved by quantifying the change in performance as given by the performance model using the SEI value, and relating it to the change in performance as measured or observed in the field, also quantified through the SEI value.

At this point, it is necessary to discuss the validity of the models used to predict performance. First, the reliability and validity of theoretically or empirically developed performance models should be considered. Second, the accuracy of the correlation between Present Serviceability Index (PSI) and ODOT's Pavement Condition Rating (PCR) should be established.

The applicability of models such as the AASHTO Design Equation

(AASHTO, 1986) is questioned due to the relatively short duration of the AASHO Road Test, the particular environment in which it was conducted, and the level of routine maintenance applied to the test section. In support of these models, Fwa and Sinha concluded that the model used to predict performance can be applied to other conditions if the differences between the test conditions and the new conditions are properly reconciled (Fwa and Sinha, 1984).

In their study, Fwa and Sinha accounted for the difference in the level of routine maintenance "... by associating pavement performance with a level of routine maintenance". The effects of environment were accounted for "... by comparing actual pavement performance curves with the performance curves predicted by AASHTO performance equations". It was proposed that a correlation between PSI and ODOT's PCR be established for the development of an equation to predict performance due to load related effects. It is argued that the accuracy of the results, obtained by using the Performance Based Approach, will suffer as ODOT personnel have had difficulty in correlating PCR and PSI. Given the tools that (1) a correlation was not established, and (2) a performance model based on PCR has not been developed, the computer model presented herein was enhanced to allow the use of a customized predicted performance equation.

Although performance models, such as the AASHTO performance equation, contain uncertainties, they are acceptable in this study because they are the best method available. Other alternatives are unacceptable for the following reasons:

- Analytical models to predict performance are difficult to develop given the current knowledge of the relationship between pavement distress and pavement performance.
- Subjective evaluations of pavement performance due to load-related factors are less reliable.

The results obtained by applying the Performance Based Approach will be affected by the inaccuracies of the particular performance model used. However, the lack of an accurate model does not affect the methodology of the Performance Based Approach; therefore, it is still acceptable. Further consideration of the accuracy of the performance models is beyond the scope of this study.

### 3.3.2 Quantification of Pavement Deterioration due to Load-Related Factors

The responsibility of various traffic loadings on pavement performance was measured by Equivalent Single Axle Loads (ESALs) during the AASHO Road Test. Mixed traffic is converted to ESAL by using ESAL factors, which by definition are "... the ratio of the number of repetitions of any axle load necessary to cause the

same amount of change in performance as one application of an 18-kip single axle load" (AASHTO, 1986). Fwa and Sinha discussed the applicability of ESALs in pavement deterioration analysis, and recommended their use as the "best" scale available to measure load effects even if ESALs include the effect of environment on pavement deterioration during the length of the AASHO Road Test.

The changes in performance from an initial serviceability level to a level predicted by the performance model, and to a level as measured in the field are shown in Figure 9. As defined in Section 3.1.2, these changes are quantified by SEI values. Hence, the change from an initial state to that predicted by the performance model is quantified by area "A". Area "A + $B_O$" would quantify the change in performance from the initial state to that measured in the field. It is likely that the change in performance estimated by the performance model is not the same as that measured in the field. Further, the performance model, as a function of load-related factors, will yield the amount of pavement deterioration due to these factors. Therefore, it is concluded that area "$B_O$" represents the amount of pavement deterioration caused by the non-load-related factors and the interaction of these with the load-related factors. Then, by direct proportion, the responsibility of each factor can be computed from:

$$e = A/(A + B_O) \qquad [3.1]$$

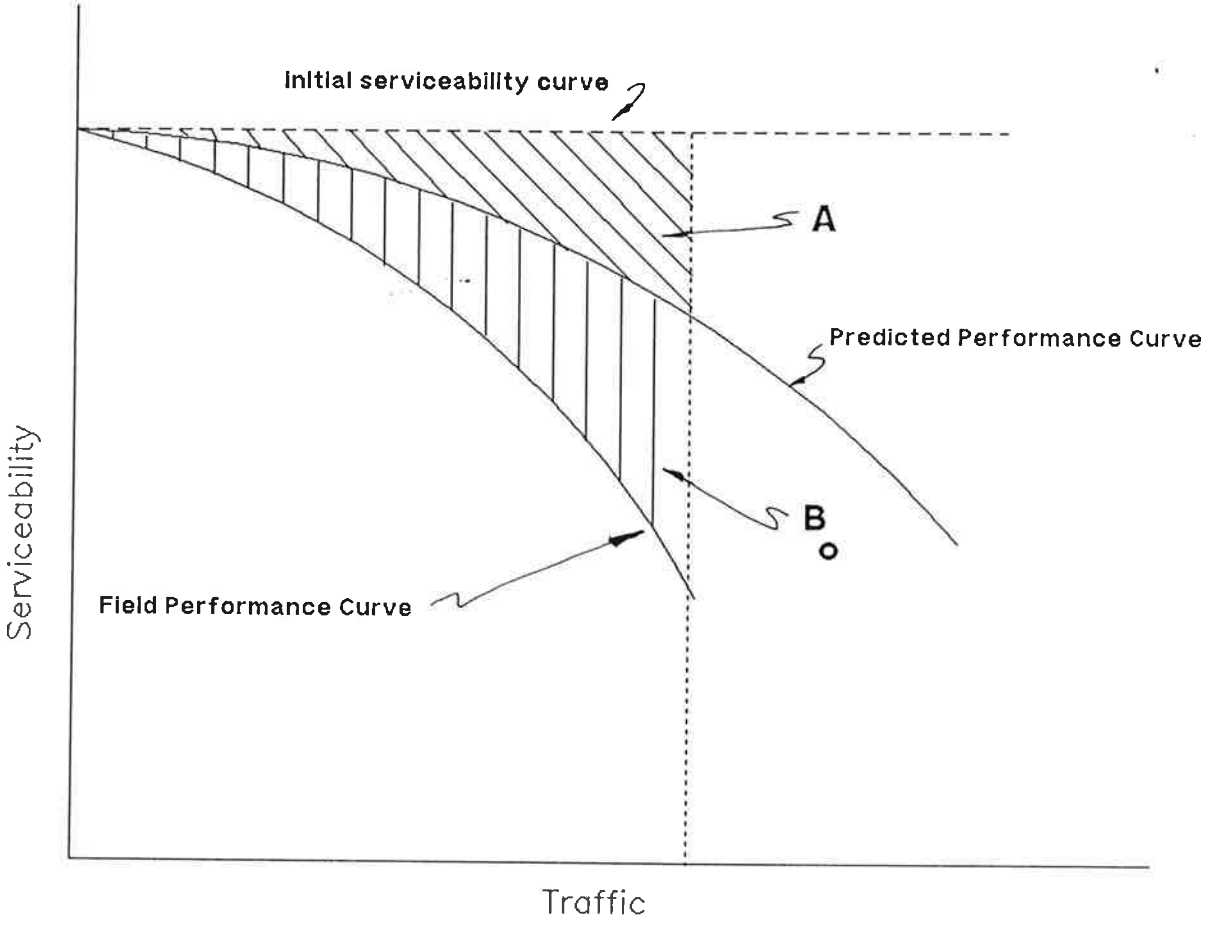


Figure 9: Effect of Load-Related Factors in Pavement Deterioration (after Fwa and Sinha, 1984)

and $$f = B_o/(A + B_o) \qquad [3.2]$$

where,

$e$ = proportion of pavement deterioration due to load-related factors.

$f$ = proportion of pavement deterioration due to non-load-related factors and interaction of these with load-related factors.

$A, B_o$ = quantification of pavement deterioration as described in Section 3.1.2.

As indicated in Section 3.1.3, routine maintenance has an effect on the total pavement deterioration as it is computed, based on field performance curves (area "$B_o$" in Figure 9). Then, neither "e" or "f" may be considered true pavement deterioration responsibilities at this point. In the following section, the effect of routine maintenance is evaluated and, its application to pavement deterioration responsibility analysis described.

### 3.4 Effects of Routine Maintenance on Pavement Deterioration

As noted in Section 3.1.1, observed distress is the result of load and non-load related factors, the interaction of the two, and the "reduction" due to routine maintenance. When routine maintenance is carried out on the pavement sections, some of the deterioration is repaired, which means that the performance measured in the field will be less than the true performance (see Figure 4).

Based on the discussion presented in the previous sections, it is reasonable to say that any field performance curve will fall

anywhere between the initial serviceability and the zero level of routine maintenance curves. Further, depending on the level of routine maintenance performed on the pavement section, the field performance curve will be closer to the initial serviceability curve for higher levels of routine maintenance. In other words, the higher the level of routine maintenance, the greater the amount of pavement deterioration repaired or the smaller the SEI.

As applied to this study, the above discussion can be used to determine the true total pavement deterioration, represented by area "A+B+C+D" in Figure 6. For this, consider a section of highway composed of a number of structurally uniform pavement sections, **n**, which have experienced the same degree of traffic loading. The only difference between the pavement sections is the level of routine maintenance carried out on each, but it is assumed that the same technology was used for the routine maintenance activities.

It is reasonable to conclude that some value, such as expenditure, can be used to quantify the level of routine maintenance, and this value will be different for each pavement section and be proportionally related to its respective level. This proportionality might be expected to be direct, i.e. the higher the level of routine maintenance the greater the expenditure.

If the performance curves, at a given time t, for the above pavement sections are plotted, as shown in Figure 10, and the SEI computed for each, it would be expected that the higher the level of routine maintenance the lower the SEI used to quantify pavement deterioration. Hence, a high SEI value would indicate that a low level of routine maintenance was performed on the pavement section. If the SEI for each performance curve of Figure 10 is plotted against the measure of the level of routine maintenance (e.g. expenditure), a relation as shown in Figure 11 would be expected. A regression line of the data set can be extrapolated to obtain the SEI value for a zero value of level of routine maintenance. As noted in Section 3.1.3, this SEI value would represent the true total pavement deterioration of the highway section for a zero level of routine maintenance, or area "A+B+C+D" in Figure 6. This result, and the result obtained in Section 3.3.2 will be used in the following section to compute the different pavement deterioration proportions described in section 3.1.4.

### 3.5 Determination of Pavement Deterioration Responsibilities

The determination of pavement deterioration responsibilities is based on the estimation of four different proportions, these being the load-related effects (defined as proportion "a"), the share of the load-related effects in the interaction effects (defined as proportion "b"), the share of the non-load-related effects in the interaction effects (defined as proportion "c"),

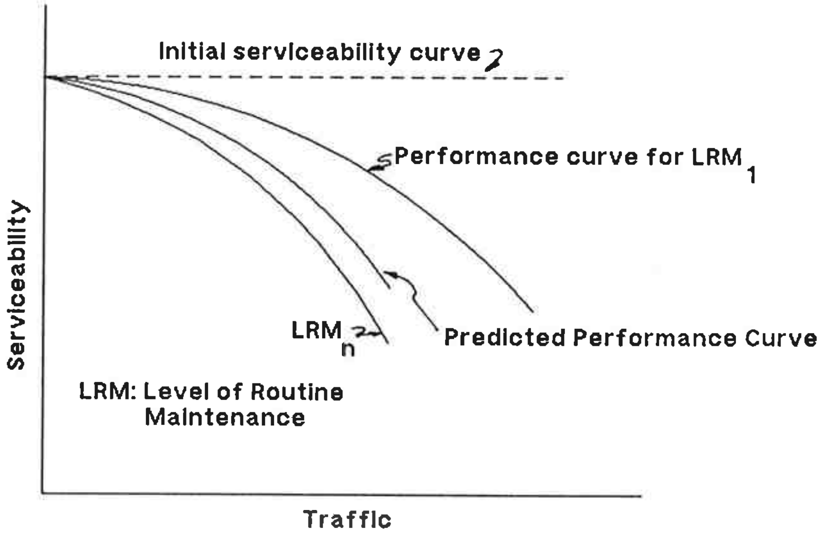


Figure 10: Performance Curves for Different Levels of Routine Maintenance (after Fwa and Sinha, 1984)

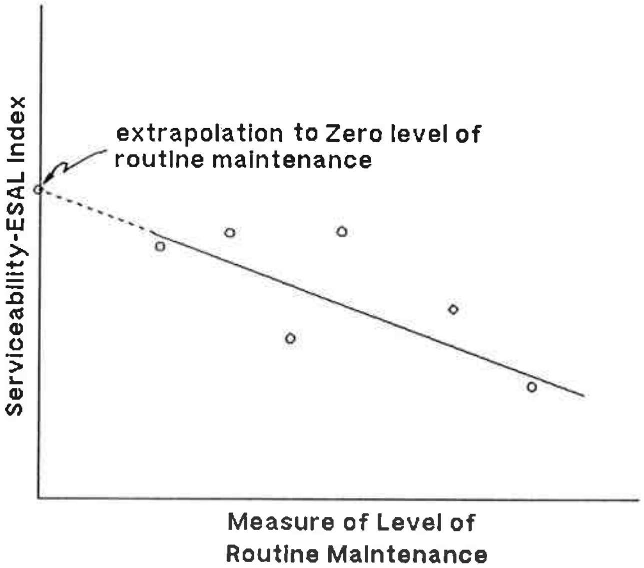


Figure 11: Relationship between Serviceability-ESAL Index and Level of Routine Maintenance (after Fwa and Sinha, 1984)

and the non-load-related effects (defined as proportion "d") (after Fwa and Sinha, 1984). In previous sections, the determination of the true total amount of pavement deterioration (area "A+B+C+D" in Figure 6), and the amount of pavement deterioration due to load related factors (area "A" in Figure 9) has been described.

Based on the two SEI values indicated above, the responsibility of purely load-related effects on pavement deterioration can be computed from the ratio of these values:

$$a = \frac{A}{A+B+C+D} \qquad [3.3]$$

where, a = percentage of total pavement deterioration caused by load-related effects alone.
A = Serviceability-ESAL Index value as computed in Section 3.3.2
A+B+C+D = Serviceability-ESAL Index value as computed in Section 3.4

For the computation of the remaining three proportions, Fwa and Sinha proposed the use of the following two proportionality assumptions, which are supported by research conducted by Sharaf (Sharaf, 1984):

$$\frac{b}{b + c + d} = \frac{a}{a + b + c + d} \qquad [3.4]$$

This assumption is interpreted as follows: the share of purely load-related effects ("a") in the total pavement deterioration

("a+b+c+d") equals the share in the interaction effects of the load-related effects ("b") in the non-load-related and interaction effects. Fwa and Sinha explained this equation as : "... for a given pavement and known set of environmental conditions and time period, the higher the traffic loading, the higher the share it is going to have in the interaction effects".

The second proportionality assumption is stated as the first for non-load-related effects, in equation form:

$$\frac{c}{a + b + c} = \frac{d}{a + b + c + d} \qquad [3.5]$$

This equation is interpreted as: the share of non-load-related effects alone ("d") in the total pavement deterioration ("a+b+c+d") equals the share in the interaction effects of the non-load-related effects ("c") in the load-related and interaction effects ("a+b+c"). Fwa and Sinha explained it as: "... for the same pavement section, the more severe the weather and other environmental conditions, the bigger is their share in the interaction effects".

Knowing that "a+b+c+d = 1" and "a", and solving for "d" in equations [3.4] and [3.5] yields:

$$d = 1 - \sqrt{1 - (1 - a)^2} \qquad [3.6]$$

Given that "a" and "d" are known from equations [3.3] and [3.6], "b" and "c" can be obtained from equations [3.4] and [3.5]. Therefore, the pavement deterioration responsibility due to load-related effects will be "a+b", and the responsibility assigned to non-load-related effects will be "c+d".

### 3.6 Discussion of Performance Based Approach

The results obtained from applying the Performance Based Approach to different highway sections within a specific region may be statistically correlated (e.g. regression analysis) with factors influencing pavement deterioration in order to create a pavement deterioration responsibility model. The methodology does not yield the responsibility of each vehicle class. This is of concern to ODOT whose cost allocation study aims at developing a fair allocation of cost responsibility to the different vehicle classes. The possibility of developing an index to be used to determine deterioration proportions based on vehicle class is not considered herein.

As discussed in previous sections, the Performance Based Approach requires that a measure of performance be identified. Currently, ODOT is collecting deflection data at several locations throughout the state. Referring to Figure 12, the theoretical deflection vs structural number curve for a pavement section can be generated by a deflection model, such as the AASHTO equation PP.26 (Appendix PP, AASHTO, 1986). From field deflection

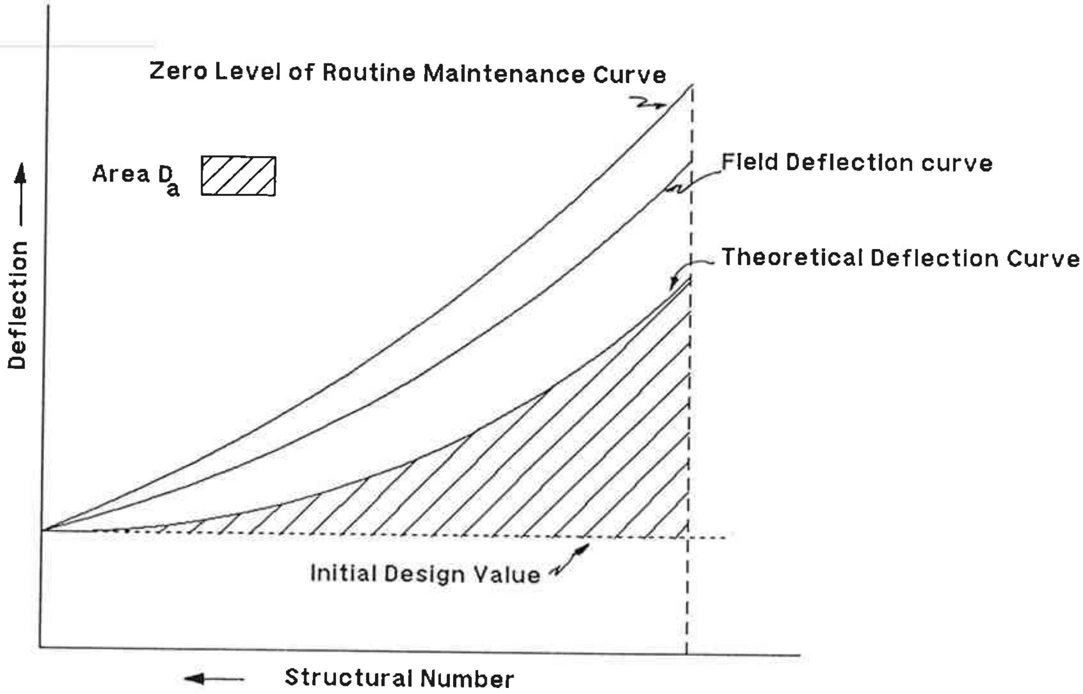


Figure 12: Performance Based Approach Based on Deflection

measurements and backcalculation procedures, data for the field deflection curve can be obtained. The area between the initial design value and the theoretical curve (area "Da" in Figure 12, equivalent to area "A" in Figure 6) is computed. The area for a zero level of routine maintenance curve can be extrapolated knowing the SEI and a quantification of level of routine maintenance for different pavement sections within the highway section. The different proportions can be computed by applying equations [3.3] through [3.6]. Further, the software package developed is capable of working with a customized performance equation. The user will have the choice of using either the AASHTO performance equations for PSI and deflection (equations 1.2.1 and PP.26, respectively, AASHTO, 1986), or entering his/her own equation to predict performance. Therefore, it is reasonable to conclude that deflection can be used to determine deterioration responsibilities.

The use of the Performance Based Approach to determine pavement deterioration responsibilities presents a number of advantages: 1) less data are required, and the data are readily available, 2) a more reliable result is obtained, and 3) the model may be updated.

In contrast to the Performance Based Approach, Utility Theory requires a substantial amount of data to develop a responsibility model. Two general types of data can be identified: subjective

and objective data. Utility Theory uses both; the subjective data to create the model, and the objective data to improve the model. The Performance Based Approach uses only objective or field data to both develop and improve the model. The subjective data for the Utility Theory may become difficult to obtain and may not be as reliable as field data. Moreover, from reviewing the responsibility studies undertaken by different agencies (Merris, 1986), it was noted that deterioration responsibilities determined subjectively varied from 0 to 100 percent. Therefore it is reasonable to conclude that subjective evaluation is not a reliable procedure.

One of the objectives of a pavement management system is the creation of an organized data base of performance and maintenance measurements. With a reliable source of information, which adapts to the requirements of the Performance Based Approach, a responsibility model can be updated, and will converge on a more accurate result.

There are two disadvantages on the application of the Performance Based Approach, these being: 1) the determination of an adequate performance measurement, and 2) the assumptions made in the approach.

This approach is structured around predicted and observed pavement performance, which in Fwa and Sinha's approach are

defined by the Present Serviceability Index (PSI) and Equivalent Single Axle Loads (ESALs) (Fwa and Sinha, 1984). The PSI values are obtained from the AASHTO design equation and from models based on roughness measurements. However, ODOT is collecting PCR data which, to be useful for this research, should be either correlated to PSI or used in performance models for defining a performance index.

Two main assumptions were made in developing Fwa and Sinha’s Performance Based Approach, namely 1) the relationship between expenditure and maintenance level, and 2) the proportionality assumptions used to compute the different deterioration responsibilities. The proportions of load versus environmental related distress will vary depending on the assumptions made and how they are interpreted.

## 4. Performance Based Approach Software

Previous sections of this report presented a methodology to be used for the creation of a pavement deterioration responsibility model. Section 3 of this report presented the Performance Based Approach. A brief introduction to the method was followed by an overview of its theoretical basis, after which the application of this method to the study was summarized. Finally, the method, and its advantages and disadvantages were discussed.

The second part of this research project consists of:

- The development of personal computer software which supports the pavement deterioration responsibility model. The systematic development of the software consists of the following phases: 1) analysis, 2) design, 3) implementation, 4) testing, and 5) maintenance. The model will be created by coding the procedure presented in this report using the BASIC programming language.
- Validation of the model using data provided by ODOT and/or data used by Fwa and Sinha (Fwa and Sinha, 1984).

When implemented by ODOT, the computer model will:

- create a database to store the data on traffic, pavement performance, routine maintenance, pavement inventory, and others for the different pavement sections analyzed,
- facilitate the process of computing the deterioration

responsibilities. This process is repetitive, for each highway section the same procedure is followed to compute the different proportions, and,

- support and facilitate the estimation of deterioration responsibilities due to load and non-load related factors for future cost allocation studies.

## 4.1 Analysis Phase

The analysis phase of the Performance Based Approach software development consists of the following steps: 1) Model Planning, and 2) Role Definition.

### 4.1.1 Model Planning

Using the Performance Based Approach, a solution strategy for the deterioration responsibility model will consist of: a database of files where the data are to be stored; an algorithm which would yield the deterioration responsibilities, plot graphics of Serviceability vs ESALs, and SEI vs a quantification of level of routine maintenance; and, an algorithm to correlate the different damage proportions with parameters significant to pavement deterioration through statistical methods.

### 4.1.2 Role Definition

The respective roles of users, hardware, and software are defined below:

- The main function of the user will be to create the database needed for the estimation of damage proportions. Further, the user will interpret the results obtained and determine their usefulness in creating the deterioration responsibility model based on their correlation to parameters significant to pavement deterioration.
- The hardware system will be formed by an IBM Personal computer, or PC compatible, and peripheral devices. Its functions are to execute the computations as ordered by the software system, store the database files, and present the results to the user.
- The software system is, first, the link between the user and the hardware system; and, second, the coded program which executes the following functions: 1) guide the user on the creation of the database, 2) process the data on the database to compute deterioration proportions, and 3) statistically correlate the deterioration proportions to the parameters significant to pavement deterioration.

## 4.2 Design Phase

As applied to this study, software design refers to the development of a general process structure for the model. This will show, in a general sense, the main processing units and their interrelation. Figure 13 sketches the process structure for the development of the pavement deterioration responsibility

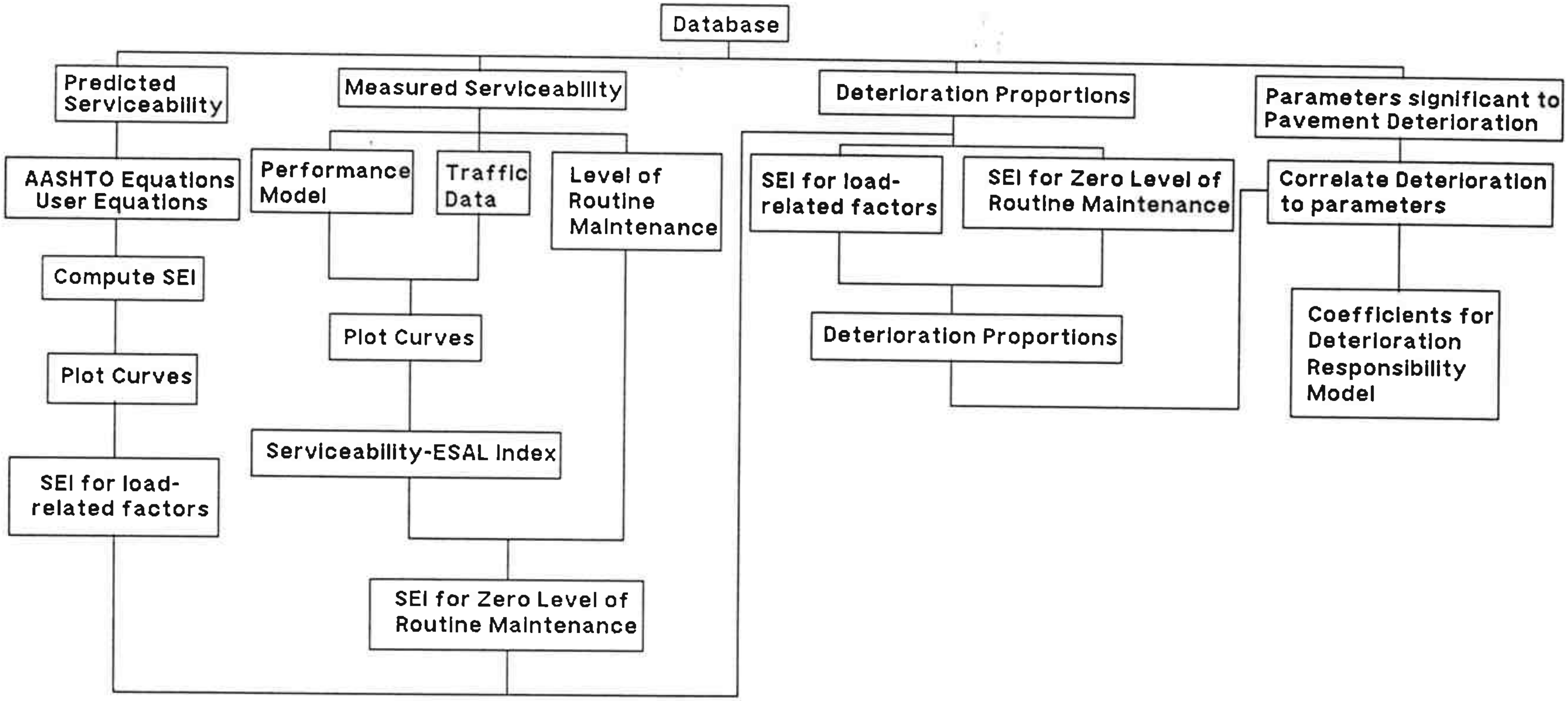


Figure 13: Structure of Performance Based Approach Software

model. The process structure is subdivided in five modules which are identified as: database, predicted serviceability, measured serviceability, deterioration proportions, and deterioration responsibility model.

The database module is to be used for entering and storing the data and information necessary as input for the other modules. Further, the results obtained are also to be stored in this module. The predicted serviceability module determines the amount of pavement deterioration due to load related factors as described in Section 3.3. The measured serviceability module determines the true total pavement deterioration by relating a measure of the level of routine maintenance to a measure of pavement performance, as described in Section 3.4. Knowing these two SEI values, the deterioration proportions, due to the factors considered, are computed, as described in Section 3.5, using the deterioration proportions module. The last module, deterioration responsibility model, correlates the deterioration proportions to a series of parameters significant to pavement deterioration. The output of this last module would be coefficients for the different parameters which compose the model.

## 4.3 Implementation Phase

The implementation of the software package consists of coding, debugging, and documenting.

Coding refers to the translation of the methodology to be used into source code using a programming language. To create the model, the BASIC programming language was selected given its widespread use and ease of understanding. To write the source code, Borland's Turbo BASIC was used because of its many advantages over Microsoft's GW-BASIC, the most important being its integrated Editor-Compiler system. The source code of the software package is presented in Volume II report.

## 4.4 Testing Phase

The system testing phase of the software package involves integration and acceptance testing. Integration refers to linking the different modules of the software into a functioning whole. In the acceptance testing subphase, a series of tests are to be planned and executed in order to demonstrate that the software product satisfies the requirements defined in the analysis phase.

## 4.5 Maintenance Phase

During the maintenance phase, the software capabilities are enhanced, the software is adapted to new processing environments, and software bugs are corrected. Proposed activities to enhance the software package are: to provide new functional capabilities, to improve software's user-friendliness, to upgrade external and/or internal documentation, and to upgrade software

performance by translating the BASIC source code to a more efficient programming language (e.g. PASCAL, C, etc.). Adapting the software to new environments refers to modification of the software package so that it can be used in other than Microsoft's Disk Operating System (MS-DOS), or IBM's PC-DOS environments. These activities are to be carried out after the software package has been used by ODOT.

### 4.6 Predicted Serviceability Module

The objective of this module is the computation of the Serviceability-ESAL Index (Section 3.1.2) based on traffic data and a predictive performance equation. The flow chart for this module is shown in Figure 14, and the source code is presented in part two of this report.

### 4.7 Measured Serviceability Module

This module will compute the Serviceability-ESAL Index based on field performance data as described in Section 3.4. The flow chart for this module is shown in Figure 15, and the source code is presented in part two of this report.

### 4.8 Pavement Deterioration Responsibilities

This module will compute the deterioration responsibilities of load and non-load related factors using the values computed by the first two modules. The flow chart for this module is shown

in Figure 16, and the source code presented in part two of this report.

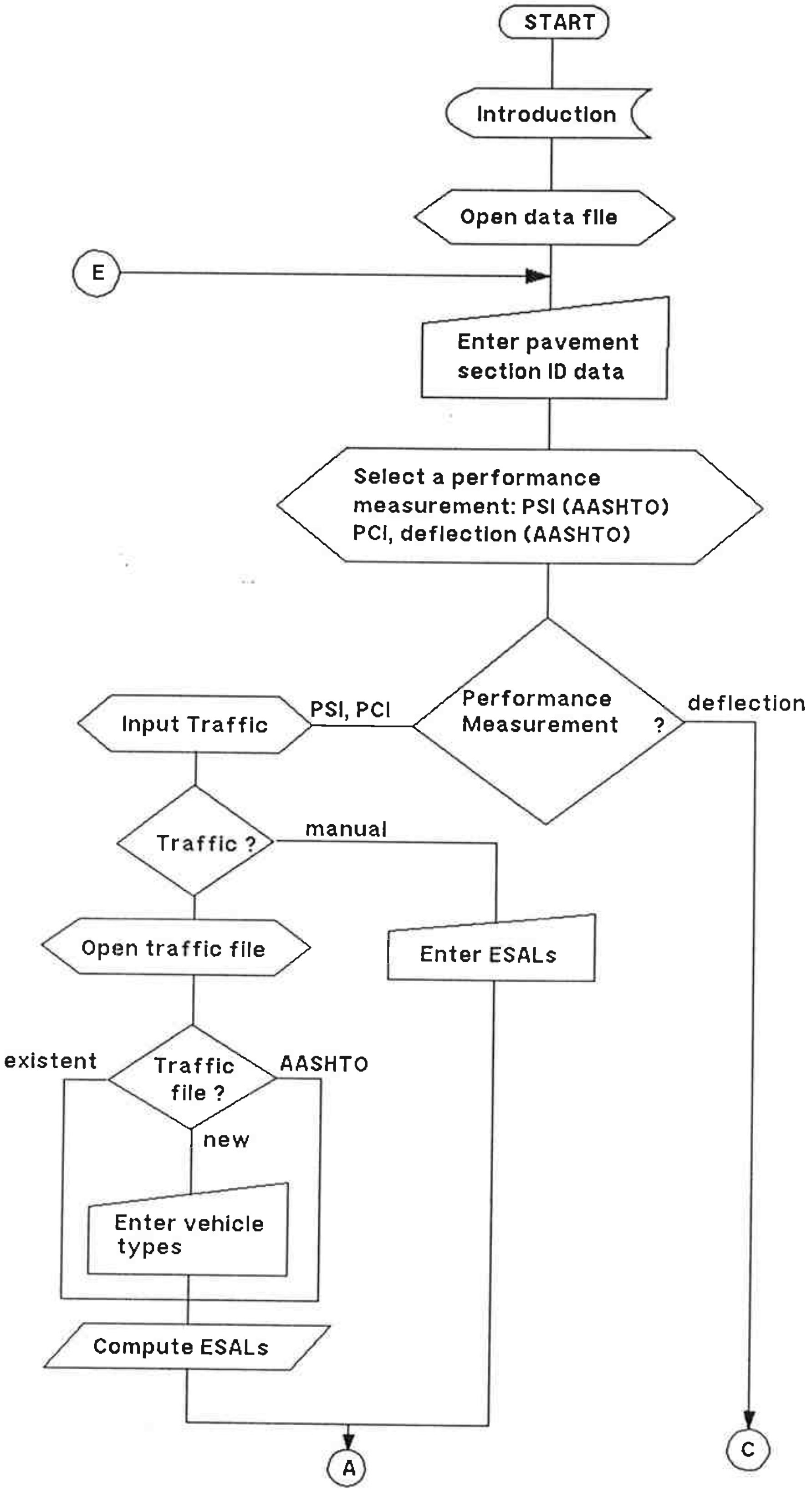


Figure 14: Flow Chart for Predicted Serviceability Module

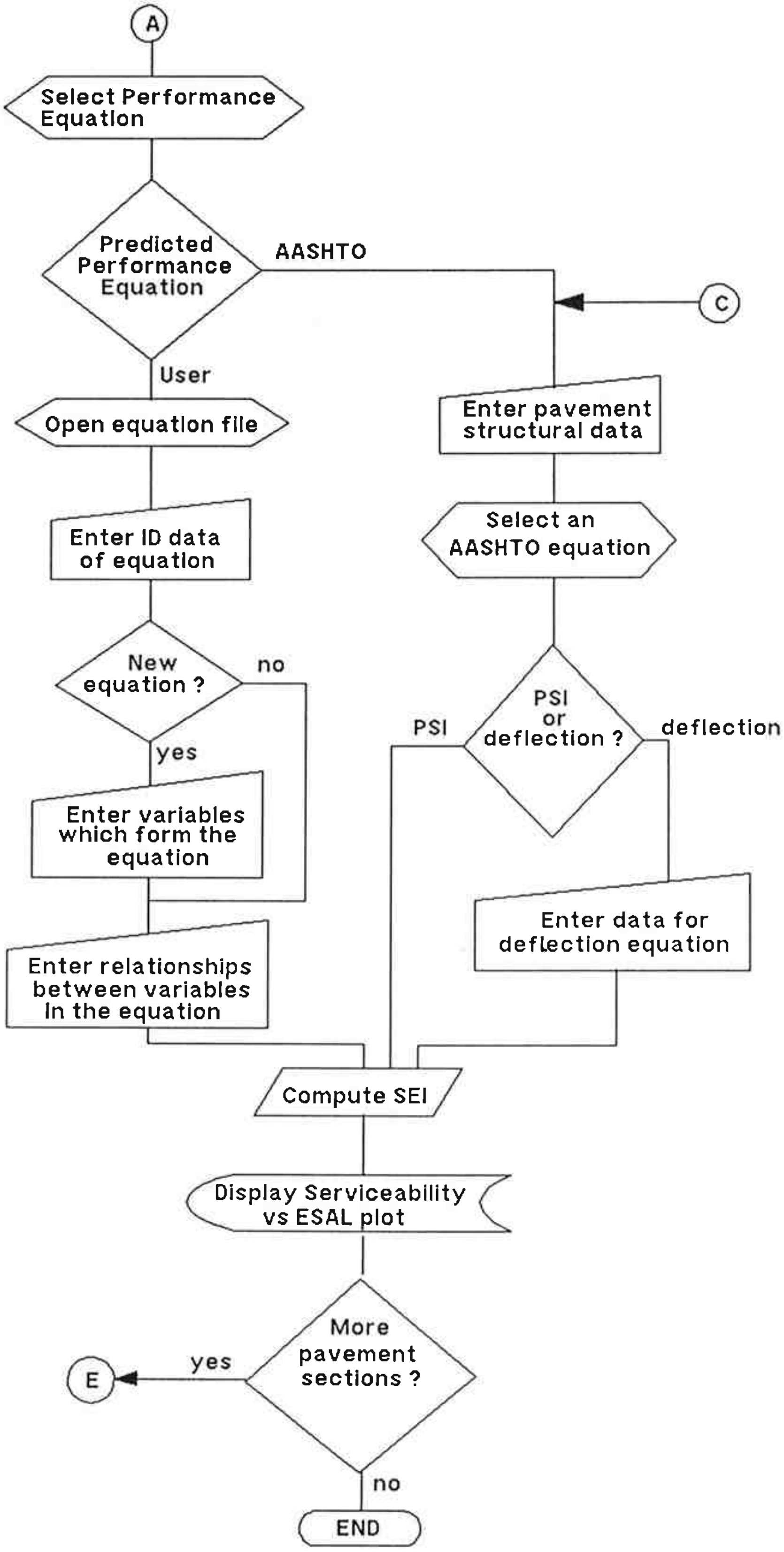


Figure 14: (cont.) Flow Chart for Predicted Serviceability Module.

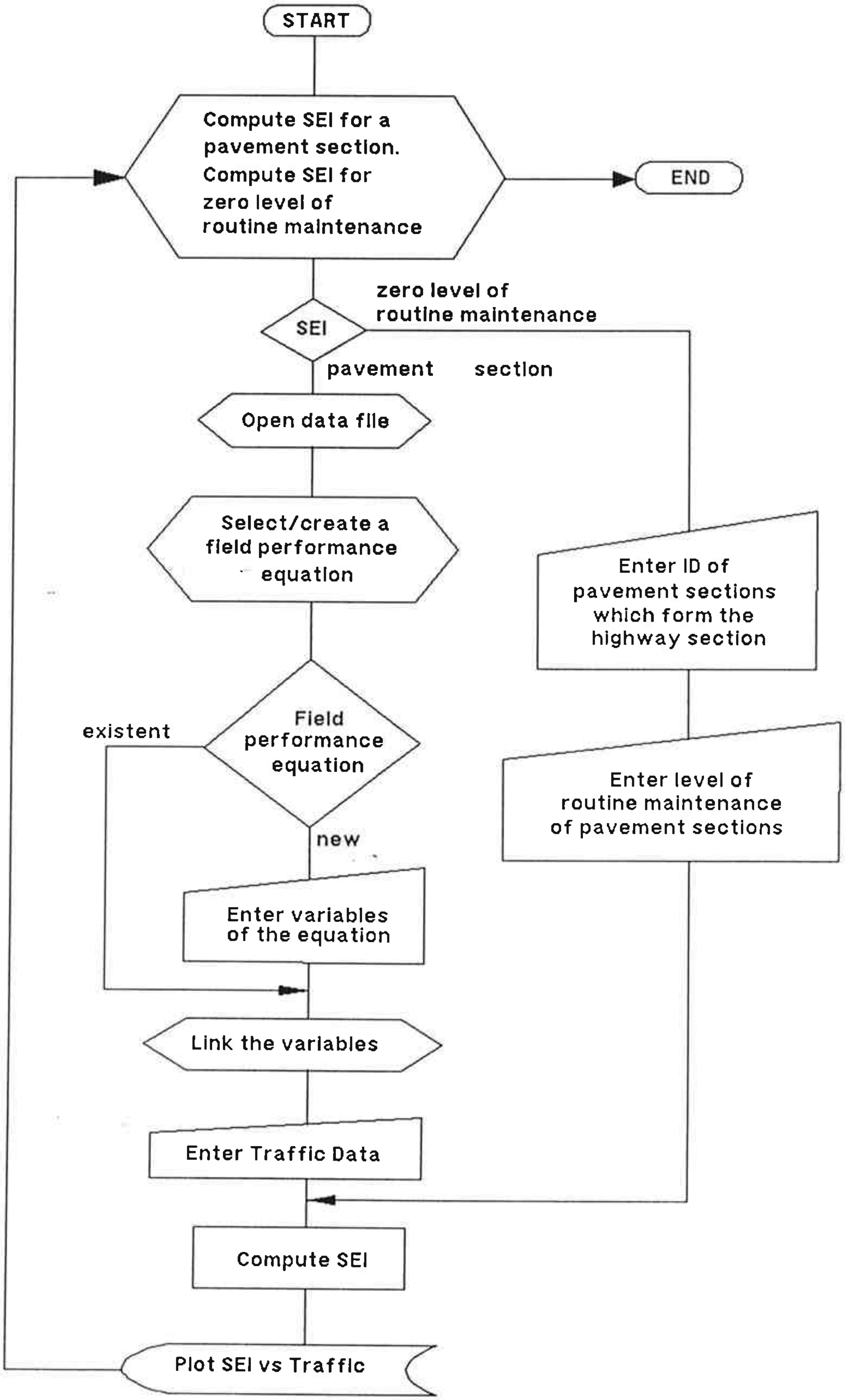


Figure 15: Flow Chart for Measured Serviceability Module

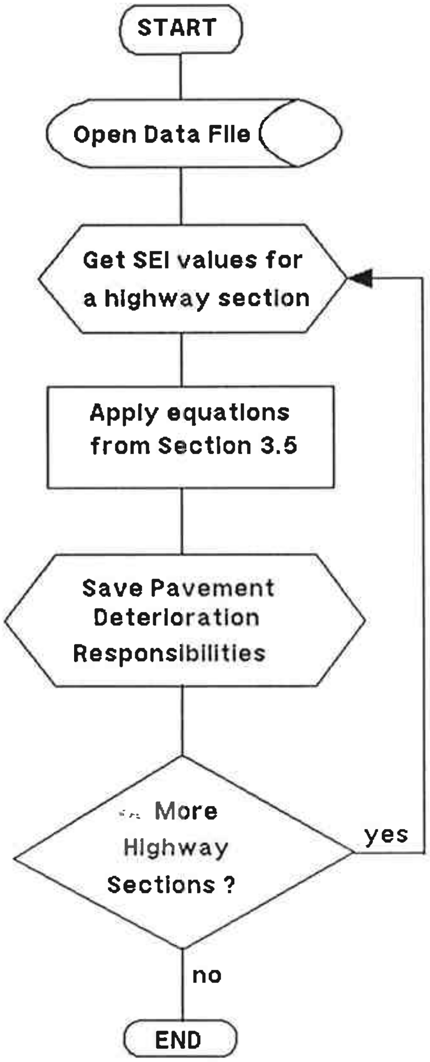


Figure 16 - Flow Chart for Pavement Deterioration Responsibilities Module

## 5. Summary

This report presents the Performance Based Approach, a procedure used in the creation of a pavement deterioration responsibility model. The theory supporting the methodology was described, and its advantages and disadvantages when applied to identify pavement deterioration responsibilities were discussed. It also described the development of the responsibility model software from a programming point of view. A general background on software development was presented, along with a brief description of the different modules which form the Performance Based Approach Software package.

The Performance Based Approach is structured around predicted and measured pavement performance, and a quantification of the level of routine maintenance. A cumulative measure of pavement deterioration, based on predicted pavement performance, is compared with a measure of pavement field deterioration, based on measured field performance. This yields the responsibility of purely load-related factors on pavement deterioration. Proportionality assumptions were made to develop equations to evaluate the share of load and non-load related factors in the interaction effects. From these assumptions, an equation to compute the proportion of pavement deterioration due to purely non-load-related factors was developed.

An alternative method, Utility Theory, is presented in Appendix A. Utility Theory is simply a structured method for organizing and using the judgement of experienced personnel. It is a conceptual model of decision making, which in its simplest form, consists of a set of alternative procedures to solve a problem, a set of parameters which define and are common to the procedures, and a set of possible outcomes which would result from applying the procedures to the problem. The theory helps the decision maker to choose among the alternative procedures, based on his/her preferences, when the outcome is uncertain. the decision maker evaluates the parameters as a function of the possible outcomes, and assigns values, called utilities, between 0 and 1 to the parameters. The combined utilities of all the parameters, or overall expected utility value, is used to rank each alternative. The best alternative procedure to solve the problem is that with the highest expected utility value.

The Performance Based Approach was selected for the final model because it applies concepts already used by ODOT, reduces subjective estimation, uses less data that are also readily available, and is believed to be more acceptable to the user. The Utility Theory was not selected as the methodology to be used in this project because of the low reliability of subjective evaluation and the complex procedure followed in applying the theory.

# Appendix A
# Utility Theory

## A.1 Utility Theory

Utility Theory is a structured method for organizing and using experienced judgement. It is a conceptual model of decision making (Raiffa, 1986), which in its simplest form consists of a set of alternative procedures to solve a problem, a set of parameters which define and are common to the procedures, and a set of possible outcomes which would result from applying the procedures to the problem.

For a given problem, the decision maker may have different techniques, methods or procedures to solve it. These are defined as alternatives in Utility Theory. The alternatives are to be evaluated against each other by identifying factors, or decision attributes, relevant to the problem, and which are common to all the alternatives.

The decision maker assigns a series of values, called utilities, to each decision attribute for each alternative. These utilities represent a subjective evaluation by the decision maker of the influence, or weight, that a factor has on the alternative being applied to solve the problem. The utilities form an interval for which one boundary represents the highest value that the factor may take when using the alternative, the other boundary represents the lowest value the factor may take. It is

recommended that utilities of 0 and 1 be assigned to the lowest and highest values of the factor, respectively.

These utilities are further used to graphically represent the influence of each decision attribute on a specific alternative. Based on the data, utility functions are defined for each decision attribute for each alternative, these functions represent the relationship between the utilities and the values of the decision attributes. Through numerical integration of these functions, a unique value is obtained for each decision attribute. This value is called the expected utility of the decision attribute.

The combination of all the expected utility values by using weighing methods or multiple linear regression, yields an overall expected utility value for each alternative. The overall expected utility values are used to rank the alternatives, and the best alternative, or solution to the problem, is defined to be that with the highest overall expected utility value.

## A.2 Methodology of Utility Theory

Utility Theory was proposed as a methodology for the creation of a pavement deterioration responsibility model. Although not the recommended approach, it is presented herein because it may have value in comparing observed pavement condition to the results of the Performance Based Approach. The theory would utilize the

judgement of experienced personnel to evaluate the responsibility of load and non-load related factors on pavement deterioration. The procedure that may be followed when using Utility Theory is sketched in Figure A-1.

The development of the Utility Evaluation Process will involve four main steps:

- Structuring the Problem
- Assessment of Utility Functions
- Identification of Uncertainties
- Selection of Best Alternative

### A.2.1 Structuring the Problem

Structuring the problem refers to the selection of the elements which form a decision, these being: a) the decision maker, b) the alternatives, and c) the decision attributes.

As applied to pavement deterioration analysis, the decision makers would be qualified individuals who, among other requirements, may have the following qualifications: 1) a minimum number of years of experience in pavement engineering, 2) experience observing the field performance of pavements, and 3) knowledge of pavement materials.

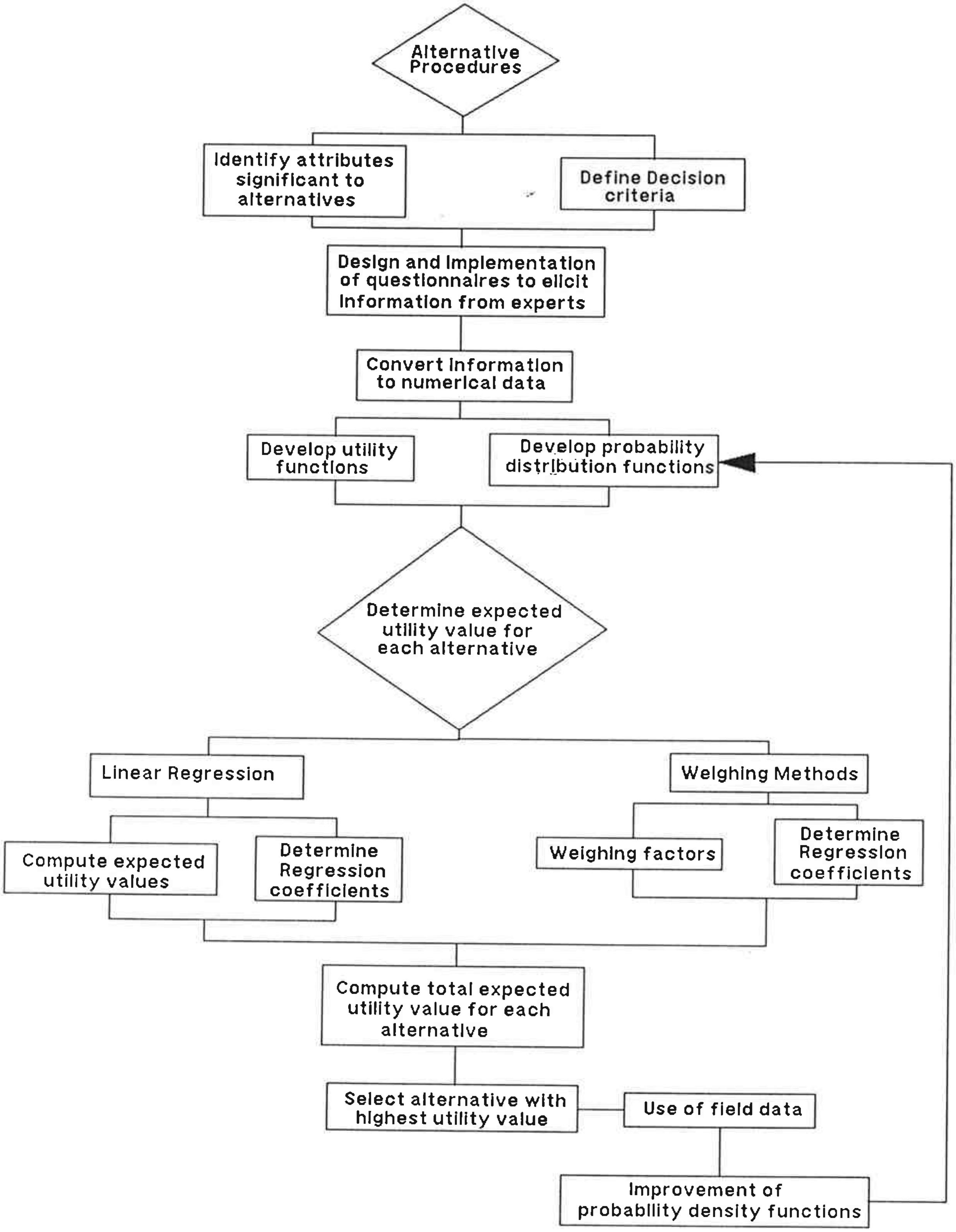


Figure A-1: Flow Diagram for the Utility Evaluation Process

The decision attributes and alternatives might include the identification of different candidate road sections with and without traffic, pavement distress manifestations with an appropriate set of measures, and cost allocations (i.e., routine maintenance through reconstruction of the pavement structure) associated with various measures and degree of pavement distress. The distress would be uniquely associated with either pavement loading under traffic or environmental factors.

### A.2.2 Assessment of Utility Functions

Selection of the best alternative is achieved after all the alternatives are ranked under the same scale. First, ranking requires quantifying the degree of preference for each decision attribute, and then computing the weighted preference of each alternative. A mathematical representation of the degree of preference for each decision attribute is given by the utility functions.

As applied to pavement deterioration analysis, a utility function might define the relationship between pavement serviceability and pavement distress. Both qualitative and quantitative information is often used to evaluate the degree of pavement distress. This information, whether qualitative or quantitative, must be related to utility of the pavement users, that is, a quantitative measure of individual preferences which can range from 0 to 1. For each pavement distress manifestation, a utility function would be

developed.

Oguara (1978) presented a procedure for assessing utility functions which is readily adaptable to engineering problems In summary, the development of utility functions "... requires conducting repeated interviews with carefully phrased questions, that reveal, by determining levels of indifference, the actual shape of the functions ...". The basis for this would be the judgement of the decision maker, which leads to a subjective development of the utility functions.

The approach used to assess the utility functions would include the following steps:

1. Determine the monotonicity of the utility function. To illustrate this concept, if an amount $x_i$ of an attribute "a" is always preferred to a smaller amount $x_j$ of "a", then the utility function is said to be monotonically increasing. The contrary, $x_j$ preferred over $x_i$, is true for monotonically decreasing functions. For example, the utility which may define area of cracking would be monotonically decreasing. Having a 20 percent area of cracking would be preferred to a 50 percent area. Defining the monotonicity of the utility functions helps to clarify the attitude of the decision maker regarding his/her preferences.

2. Establish the upper and lower limits of the interval defining the utilities. This interval would represent the preferences of the decision maker, and evaluate them on a scale of zero to one. A value of one is usually assigned to the most desirable amount of an attribute, and zero to the least desirable. For example, to a PSI value of 4.2 a utility of 1 can be assigned, and for a PSI of 2.5 a utility of 0.

3. Determine the magnitudes of the attribute for which the decision maker will assign a mean utility value of 0.5, and utility values of 0.34 and 0.66 (mean +- 0.16). Utility functions which represent quantitative decision attributes can be defined by a five-point approximation. Qualitative functions would require a three-point approximation (Oguara, 1978). The utilities are plotted against their respective amounts of the decision attribute, and a curve is fitted through the points defining the utility function.

### A.2.3 Determination of Uncertainty

For any engineering project, the exact evaluation of a parameter is not possible. This is because the knowledge of the real situation is incomplete. Uncertainty will exist when a parameter value is estimated based on a practical sample size or on experience. Overcoming this will require a very large sample

size which is impractical and expensive. As applied to pavement deterioration analysis, the magnitude of distress and cost estimates have an associated degree of uncertainty. It is probably true that the degree of distress has greater uncertainty than the estimate of cost associated with maintenance/ reconstruction relative to distress.

Utility Theory accounts for the uncertainty involved in the estimates of each decision attribute by using probabilistic analysis. Hence, the uncertainty can be represented by a probability distribution function (pdf). Given that the decision variables are represented as a distribution of values, the use of probability distribution functions ensures more confidence by taking into account the variability of the parameter in the field.

Given its applicability, it is recommended that the Beta pdf be used when a variable is bounded at both upper and lower ends. Furthermore, the shape of the function can be modified by varying its distribution parameters. The Beta pdf is computed based on optimistic or low, most probable, and pessimistic or high estimates of the decision attribute. These estimates are obtained from carefully phrased questions given to the decision maker.

The utility curve obtained in Section A.2.2, is multiplied with the pdf to obtain the expected utility function for each decision attribute. The area, bounded by this last curve computed through integration methods, is defined as the overall expected utility value for the decision attribute.

### A.2.4 Selection of Best Alternative

In the first three steps, the decision attributes, the probability distribution over the attributes, and the overall expected utility of each attribute was defined and quantified. The next step is to compute the combined utility for all the attributes of an alternative. This can be achieved by either of two methods:

1. Additive Weighing Method:

$$E(u)_i = \sum_{i=1}^{n} W_i \, U_i(x) \qquad [A-1]$$

where,

$E(u)_i$ = expected utility value of alternative i.
$W_i$ = weighing factor which represents the relative weight of the $i_{th}$ attribute as defined by the decision maker.
$U_i(x)$ = expected utility value of the $i_{th}$ attribute, obtained in A.2.3.

2. Multiple Linear Regression:

$$E(u)_i = e^{a_o} \, (U_1)^{a_1} \cdots\cdots\cdots (U_n)^{a_n} \qquad [A-2]$$

where,

$E(u)_i$ = expected utility value of alternative i.
$a_o, .., a_n$ = regression coefficients
$U_i$ = expected utility value of the $i_{th}$ attribute, obtained in A.2.3.

The main difference between the two methods is that the regression method assumes some interaction among the decision attributes, while the weighing method assumes no interaction.

The best alternative will be the one with the highest expected utility value, $E(u)_i$, as obtained from either [A-1] or [A-2]. As applied to pavement deterioration analysis, this value would represent the expected utility cost allocations.

### A.3 Discussion of Utility Theory

The Utility Theory is based upon a quantification of engineering judgement through utility functions. Uncertainty involved in the evaluation of the functions is estimated by probability distribution functions. Linear Regression or Additive Weighing Methods are then used to select the best alternative to solve a problem.

The application of Utility Theory to pavement deterioration responsibility analysis may present a number of advantages :

1. Any number of factors can be combined and evaluated using the same scale. The subjective information is given a numerical value ranging from 0 to 1, depending on the preference of the decision maker. Then, by evaluating each decision attribute in a common scale, they may be combined and the result used to rank each

alternative on a common framework. Furthermore, the number of attributes is not limited by the procedure, but by the ability of the decision maker to correlate the attributes.

2. The model may be updated by using objective data. The model can be improved by updating the probability distribution functions, converging towards a more accurate solution. This can be achieved by using Bayes' rule.

3. Subjective data are obtained from experienced personnel. In the past, ODOT has established pavement deterioration responsibilities of load and non-load related factors based on a non-structured judgement of experienced personnel. Utility Theory applies the cumulative experience of highway personnel to systematically develop a model that can be updated in the future.

The principle disadvantages of the application of Utility Theory are:

1. The selection of assessors and experienced personnel. Application of Utility Theory to the determination of deterioration responsibilities would require knowledge of probability and statistics, and of methods to elicit adequate information from the decision maker. This may

require consulting with assessors knowledgeable in these fields, which may not include staff members of the highway department. Further, staff personnel may require additional training on evaluating the uncertainty involved in later improvements of the probability functions.

Assessors familiar with methods of eliciting expert opinions may be needed. The questionnaires should be composed of questions which can be responded to by the personnel. Furthermore, the answers shall be reviewed to determine their accuracy and validity. Several reasons for this are: difference in opinion among experts, lack of verification with field data, and biased assessments. Therefore, an expert on analysis of subjective data should be involved in the project.

The selection of experienced personnel may present some difficulties. First, there is a problem identifying personnel with adequate experience on pavement deterioration. Second, an adequate statistical data base is required to achieve a representative value. Hence, it is recommended that the number of data sources which are statistically representative be determined. This will directly affect the number of experienced personnel needed. Finally, the subjective data shall be

analyzed, as previously noted, rejecting the information which is not consistent with the group's tendency. This will further increase the number of sources needed.

2. The number of variables considered in the model. Utility Theory does not limit the number of variables used in the methodology; however, the process of interrelating a large number of variables may become complex and misleading. On the other hand, a small number of variables may not be representative of those significant to pavement deterioration. This would require a more carefully planned methodology; first, by selecting and ranking the most significant variables and, second, by structuring the questionnaires around these variables and their interaction. This will make the development of the utility functions a complex task.

3. The subjective determination of deterioration responsibilities. Utility Theory uses the judgement of experienced personnel to evaluate deterioration responsibilities. As pointed out, this might bring some disadvantages: biased assessments, careless thought given to the assessments, and difference in opinion among experts. Although the use of the theory will provide a more reliable result than that obtained solely from the judgement of highway personnel, the feasibility of using

this method should be evaluated against the accuracy obtained.

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