
PREDICTION MODELS OF DISTRESS FOR CONCRETE PAVEMENTS: A EUROPEAN EXPERIENCE

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INTRODUCTION

Since 1980 a great effort has been made in the USA to develop distress models to predict concrete pavement performance. In Europe, a research group has been working since the beginning of the current decade, under the auspices of the Technical Committee 7 (Concrete Roads) of the Permanent International Association of Road Congresses (PIARC), trying to develop distress models for concrete pavements valid for European conditions. The group consisted of researchers from five European countries: Belgium (B), Great Britain (GB), Italy (I), France (F) and Switzerland (CH). During the project close collaboration with USA experts has been maintained.

This paper refers to the participation of Switzerland in this research project, which has been executed by Betonstrassen AG in Wildegg. The paper presents the main results of the research work. The full results, along with the whole project documentation have been presented in a recent Swiss publication by Wilk and Tsohos (1).

STATE OF THE ART

Based on USA experience, the factors influencing the distresses developed in a concrete pavement have been defined in this research project as follows:

1. the age of the pavement,
2. the thickness of the concrete slab,
3. the type of the pavement base /subbase and
4. the traffic loads.

The distress models used are those developed by Darter et al (2-4). Additionally, the cracking models developed by ERES (5) and during the SHRP projects (6) and the faulting models according to ERES (5), Tsohos (*unpublished data*), Ioannides et al (7) and Snyder et al (8), have been used. As far as present serviceability index is concerned, a simple prediction model has been developed by the authors, based on the equations presented in the paper of Kilareski and Krammer (9).

COLLECTION OF DATA

Data have been collected either for the evaluation and modification of the existing models or for the development of new models for concrete pavement distress performance. The data collection procedure has been designed carefully so that it:

1. covers the various climatic conditions of the country,
2. represents all the construction types in use,

3. covers the maximum possible spectrum of traffic loads (expressed in ESAL) and
4. takes into account the parameter of pavement aging.

The roads selected have a total length of 120 km. They cover 4 out of the 6 climatic regions of Switzerland (in the rest 2 climatic regions, in which the terrain is mostly mountainous, there are no concrete pavements). From this road pavement database, a considerable number of the so called 'homogeneous sections' has been selected, in order to cover the previously set criteria. Each section has a length of 200 m. Totally 106 homogeneous sections have been selected. This represent 16% of the total concrete pavement length of the country, a sample which is, by far, statistically sufficient for the evaluation of any influencing parameter.

It should be mentioned that in certain Swiss Cantons data concerning pavement performance have been meticulously gathered for over 40 years. In any case recent measurements have been taken especially concerning cracks and faultings for which existing data were not available to the desired extent.

In the other European countries comprising the research group, relative measurements were much less available. Gathering the necessary data is the main reason for their delay to present prediction models of concrete pavement performance yet.

Figure 1 shows the distribution of the selected road sections according to pavement age, slab thickness, type of base and cumulative traffic.

Figure 2 presents the comparison of the Swiss selected road sections with those selected in the rest European countries participating in the research project. It worth's mentioning that in Switzerland and France most concrete pavements are constructed on unbound granular bases, whereas in Great Britain, Belgium and Italy most concrete pavements are laid on top of cement stabilized bases. More detailed information is given by Wilk and Tsohos (1).

EVALUATION OF THE APPLIED DISTRESS MODELS

The evaluation of the selected distress models consisted of two workpackages:

1. A sensitivity analysis part, to identify the importance of any factor involved in each equation of the models. The reasoning of this work was to simplify, if possible, the structure of the models. A sensitivity analysis of the pumping model for instance, demonstrates the influence of the design factors to the pumping distress change. This analysis showed that concrete slab thickness is, as expected, the most significant parameter: a small increase in slab thickness reduces considerably pumping potential. Traffic loads (expressed in ESALs) is another important parameter. On the other hand, the mean annual rainfall and the frost index (FI) have a smaller influence to pumping potential (Darter (2,4)).
2. The applicability of the distress models in the selected sections. The scope of this workpackage was to investigate the possibility of plain application of the selected models or the need for modifications.

The distress models selected for evaluation are presented in Table 1.

The complete set of results concerning the comparison between the values of the presented models in Table 1 and the measured values in the selected road sections can also be found in Wilk and Tsohos (1).

Figures 3, 4 and 5 have been selected for presentation to demonstrate some representative comparison curves concerning pumping, joint distress and faulting. It should be commented for Figure 3 (pumping) that only the minimum model values approximate the observed field values, hence the need for model modification is obvious.

The authors concluded to modify the distress models given in Table 2.

It should be mentioned that there is no correlation between the observed field values and the prediction of the models for cracking. Therefore no cracking model has been found suitable for modification.

MODIFICATION OF DISTRESS MODELS

An iteration procedure has been used to modify the selected distress models. The limits in which each model yield accurate results have been taken into account. The work has been completed in a personal computer. Detailed results of this research entity are given in Wilk and Tsohos (1).

Representative results of the modification procedure of the distress models are presented in Figures 6, 7 and 8. Figure 6 refers to the modification of the model for pumping to fit observed field data. Figure 7 refers to the model of spalling prediction at joints and Figure 8 to the variation of PSI value with pavement aging.

It should be emphasized that for certain models (as joint distress and faulting) it has been developed more than one alternative equations describing the development of distresses under various conditions.

In Table 3 all the modified models are summarized.

The other participating European countries have not yet published results concerning distress models. Thus, any comparison and relevant evaluation of the models is postponed for the near future.

CONCLUDING REMARKS

Switzerland is the first country of the European research team which, having concluded the research, proposed prediction models of distress for concrete pavements. In Belgium, Great Britain, Italy and France research is under completion. The proposed models (and the ones to come) will become a valuable tool for the evaluation of concrete pavement performance under certain European conditions and for the suitable updating of concrete pavement design procedure as well.

Apart from the distress models presented in Table 3., the research work also confirmed the following general conclusions:

1. Existing distress models cannot be applied in other countries or even in other regions with different climatic conditions, without being verified or calibrated.
2. The modification of existing or the development of new distress models require a great amount of data, over a long period of time.
3. The proposed modified distress models should not be considered as the final ones. Further investigation is needed to secure their validity.

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TABLE 1 Tested Distress Models for Concrete Pavements.

TABLE 2 Distress Models for Concrete Pavements Selected for Modification.

TABLE 3 Modified Distress Models for Concrete Pavements for Application in Switzerland.

TABLE 1 Tested Distress Models for Concrete Pavements

Type of distress	Reference	Mathematical Formulation of the Model
1. Pumping	(2 - 4)	$\text{PUMP} = \text{ESAL}^{0.443} \times [-1.479 + 0.255 \times (1 - \text{SOILCRS}) + 0.0605 \times \text{SUMPREC}^{0.5} + \frac{52.65}{\text{THICK}^{1.747}} + 0.0002269 \times \text{FI}^{1.205}]$ (1)
2. Joints	(2 - 4)	$\text{DETJT} = \text{AGE}^{1.695} \times (0.9754 \times \text{DRACK}) + \text{AGE}^{2.841} \times (0.0127 \times \text{UNITUB}) + \text{AGE}^{3.0038} \times (0.001346 \times \text{INCOMP})$ (2)
	(6)	$\text{SPALLJT} = 9.79 + 10.09 \times [-1.227 + 0.0022 \times (0.9853 \times \text{AGE} + 0.1709 \times \text{FI}^2)]$ (3)
3. PSI	(9)	$\text{PSI} = 4.19 - 0.0394 \times \text{AGE}$ (4)
	(2)	$\text{PSI} = 4.5 - 1.486 \times \text{ESAL}^{0.1467} + 0.4963 \times \text{ESAL}^{0.265} \times \frac{\text{SUMPREC}^{0.91}}{\text{AVGMT}^{1.07}} \times \text{RATIO}^{-0.5} - 0.01802 \times \text{ESAL}^{0.644} \times \text{AGE}^{0.525}$ (5)
4. Cracking	(2, 3, 4)	$\text{CRACKS} = \text{ESAL} \times 2.755 \times [3092 \times (1 - \text{SOILCRS}) \times \text{RATIO}^{10} + \text{ESAL}^{0.5} \times (1.233 \times \text{TRANGE} \times \text{RATIO}^{2.568}) + \text{ESAL}^{2.416} \times (0.2296 \times \text{FI}^{1.58} \times \text{RATIO}^{7.31})]$ (6)
	(8)	$\text{TR} = \frac{1}{0.01 + 0.0713 \times 2.549^{-\log(\text{FD})}}$ (7)
5. Faulting	(2, 3, 4)	$\text{FAULT} = \text{ESAL}^{0.144} \times [-0.298 + 0.2671 \times \frac{1}{\text{THICK}^{0.3184}} - 0.0285 \times \text{BASETYP} + 0.00406 \times (\text{FI} + 1)^{0.3589} - 0.0462 \times \text{EDGESUP} + 0.2384 \times (\text{PUMP} + 1)^{0.0109} - 0.034 \times \text{DOW}^{2.0587}]$ (8)
	(8)	$\text{FAULT} = \text{ESAL}^{0.7419} \times (0.03641 - 0.002921 \times \text{BASE}) + 0.2754 \times (\text{AGE} \times \text{FI})^{0.01898} - 0.2834$ (9)

PUMP: A variable evaluating pumping (any value between 0 to 4: 0 for no pumping, 4 for intense pumping)
 ESAL: 1 ESAL = 8.2 t
 SOILCRS: A variable evaluating type of soil (0 for fine-grained soil and 1 for coarse-grained)
 SUMPREC: Mean annual rainfall in cm
 THICK: Slab thickness in inches
 FI: Frost Index expressed in number of days of frost
 DETJT: Number of worn joints per mile
 AGE: Pavement age
 DRACK: Cracks at slab corners (1 for the existence of cracks and 0 for nonexistence)
 UNITUBE: A variable evaluating special construction measures for joint protection (1 for the existence of special joint protection and 0 for nonexistence)
 INCOMP: A variable evaluating the condition of the asphaltic mastic sealing the joint (1 if the asphalt mastic is in good condition, 0 if it is not)
 SPALLJT: Percentage of spalled joints
 PSI: Present serviceability index
 RATIO: The ratio of developed to maximum allowable stresses
 AVGMT: Mean monthly temperature in Celsius degrees centigrade
 CRACKS: Total length of cracks measured in feet per lane-mile
 TRANGE: Difference in average monthly temperature between the hottest and the coldest month of the year
 TR: Transverse crackings expressed as a percentage of the total crackings
 FD: Ratio of the number of ESALs trafficked the pavement to the design number of ESALs for the pavement
 FAULT: Faulting expressed in inches
 BASETYP: Type of pavement base (1 for stabilized base and 0 for non-stabilized)
 EDGESUP: Type of shoulder (0 for asphalt concrete shoulders and 1 for any other type of shoulder)
 DOW: Diameter of dowel bars in inches
 BASE: As BASETYP

TABLE 2 Distress Models for Concrete Pavements Selected for Modification

Type of distress	Reference	Equation
1. Pumping	(2, 3)	(1)
2. Joints	(2, 3, 6)	(2)
3. PSI	(9)	(4)
	(2)	(5)
4. Faulting	(8)	(9)

TABLE 3 Modified Distress Models for Concrete Pavements for Application in Switzerland

Type of distress	Equation	Mathematical Formulation of the Model
1. Pumping	(1)	$\text{PUMP} = \frac{\text{ESAL}^{0.39} \times [-1.342 + 0.538 \times \text{SUMPREC}^{0.3607} + 41.41]}{\text{THICK}^{1.993}} + 0.00211 \times \text{FI}^{1.104}$, standard error: ± 0.34 (10)
2. Joints	(2)	$\text{DETJT} = 0.199 \times \text{AGE}^{1.339}$, standard error: ± 3.8 (11) For pavement age < 20 years: $\text{DETJT} = 0.06 \times \text{AGE}^{2.15} + 0.0005 \times \text{AGE}^{2.35}$, standard error: ± 3.0 (12) For pavement age > 20 years: $\text{DETJT} = 0.06 \times \text{AGE}^{2.17} + 0.0008 \times \text{AGE}^{2.58}$, standard error: ± 4.5 (13)
3. PSI	(4)	$\text{PSI} = 4.32 - 0.0266 \times \text{AGE}$, standard error: ± 0.14 (14)
	(5)	For pavement age < 20 years: $\text{PSI} = 4.5 - 1.28 \times \text{ESAL}^{0.13} + 0.55 \times \frac{\text{ESAL}^{0.275} \times \text{RATIO}^{-0.5} - 0.008 \times \text{ESAL}^{0.62} \times \text{SUMPREC}^{0.85}}{\text{AVGMT}^{1.1}} \times \text{AGE}^{0.525}$, standard error: ± 0.27 (15) For pavement age > 20 years: $\text{PSI} = 4.5 - 1.886 \times \text{ESAL}^{0.13} + 0.55 \times \frac{\text{ESAL}^{0.275} \times \text{RATIO}^{-0.5} - 0.008 \times \text{ESAL}^{0.62} \times \text{SUMPREC}^{0.85}}{\text{AVGMT}^{1.8}} \times \text{AGE}^{0.525}$, standard error: ± 0.18 (16)
4. Faulting	(9)	For (pavement age) $\times$ (FI) < 7000: $\text{FAULT} = \text{ESAL}^{0.5} \times (0.03641 - 0.002921 \times \text{BASE}) + 0.27 \times (\text{AGE} \times \text{FI})^{0.0008} - 0.2834$, standard error: ± 0.84 (17) For (pavement age) $\times$ (FI) > 7000: $\text{FAULT} = \text{ESAL}^{0.8} \times (0.03641 - 0.002921 \times \text{BASE}) + 0.27 \times (\text{AGE} \times \text{FI})^{0.0008} - 0.2834$, standard error: ± 1.92 (18)

PUMP: A variable evaluating pumping (any value between 0 to 4: 0 for no pumping, 4 for intense pumping)
ESAL: 1 ESAL = 8.2 t
SUMPREC: Mean annual rainfall in cm
THICK: Slab thickness in inches
FI: Frost Index expressed in number of days of frost
DETJT: Number of worn joints per mile
AGE: Pavement age
PSI: Present serviceability index
RATIO: The ratio of developed to maximum allowable stresses
AVGMT: Mean monthly temperature in Celsius degrees centigrade
CRACKS: Total length of cracks measured in feet per lane-mile
FAULT: Faulting expressed in inches
BASE: Type of pavement base (1 for stabilized base and 0 for non-stabilized)

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- FIGURE 1a** Participation (%) of selected concrete road pavement sections according to pavement age.
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FIGURE 5 Model values (max - min) and measured values for faulting.

FIGURE 6 Model modification for pumping to fit observed field data.

FIGURE 7 Model modification for spalling at joints to fit observed field data.

FIGURE 8 Model for PSI values variation due to pavement aging to fit observed field data.

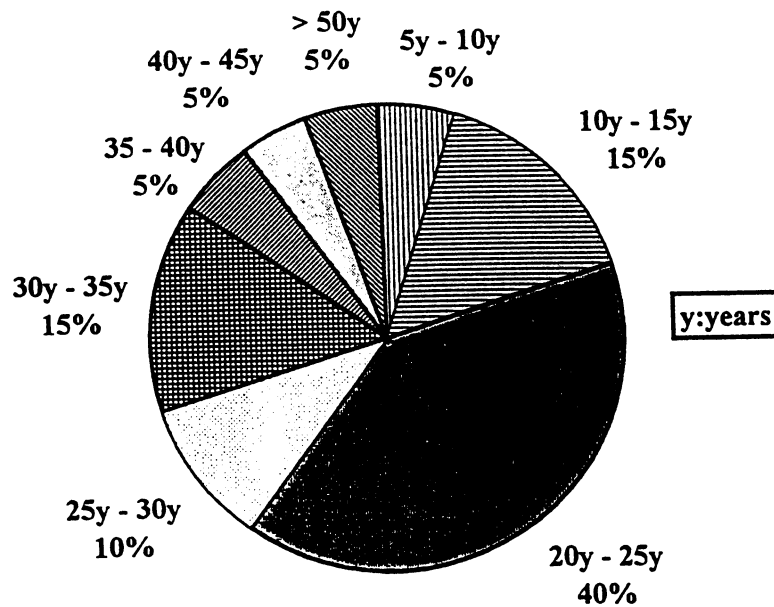


FIGURE 1a

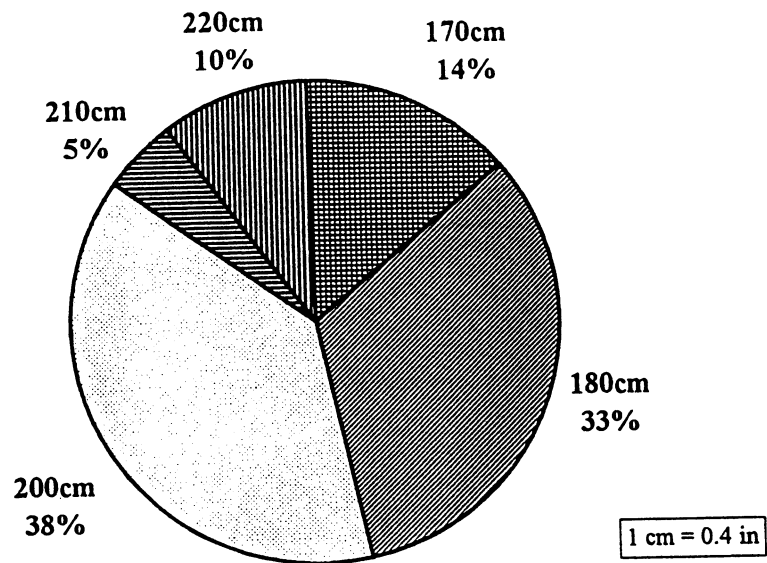


FIGURE 1b

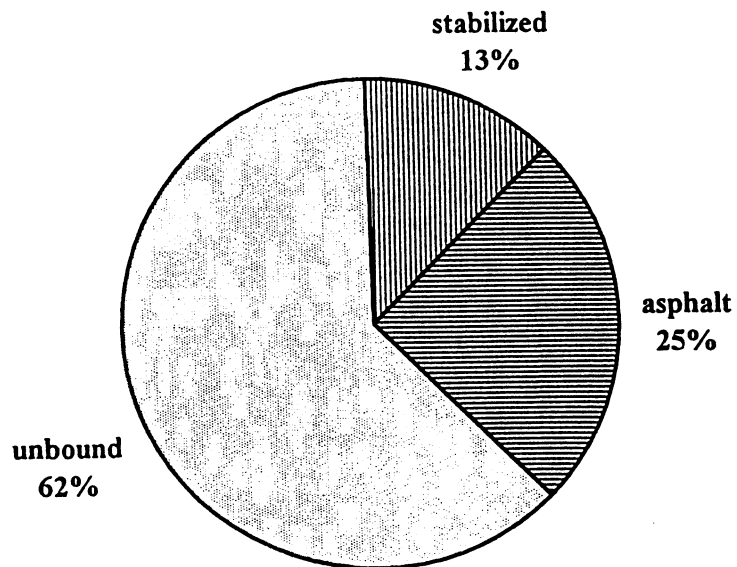


FIGURE 1c

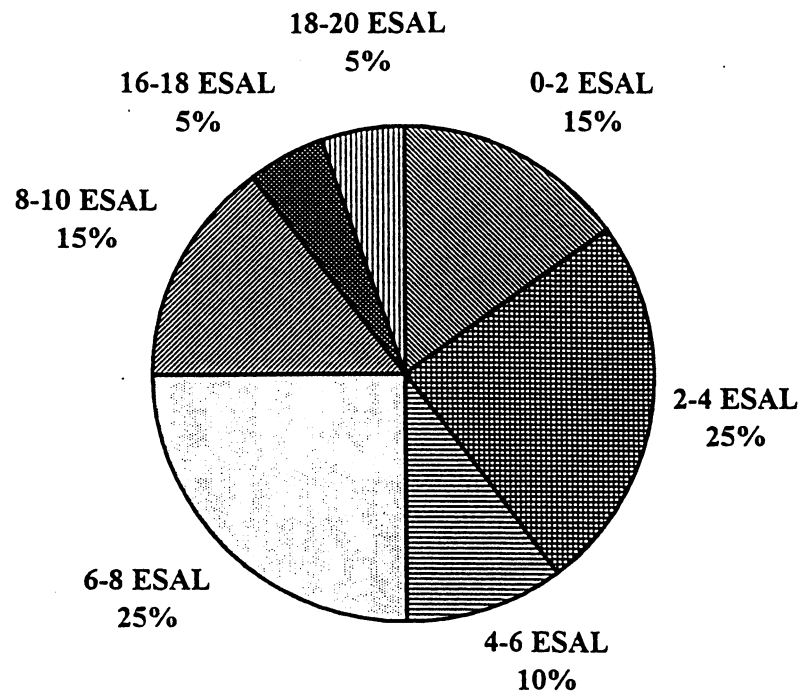


FIGURE 1d

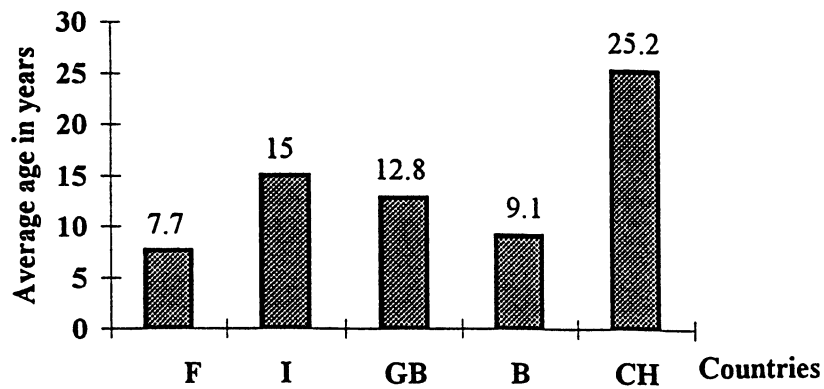


FIGURE 2a

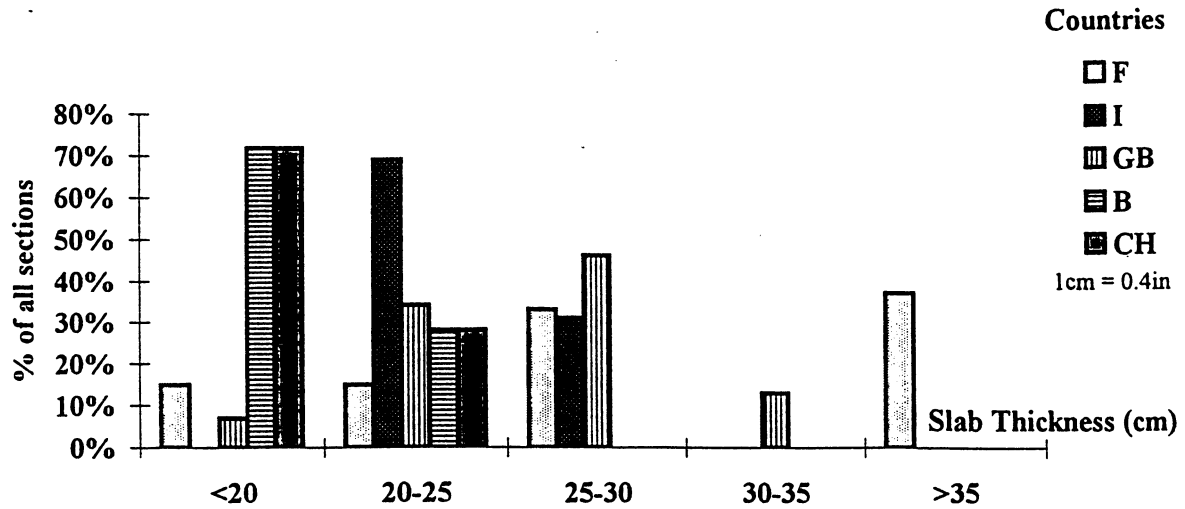


FIGURE 2b

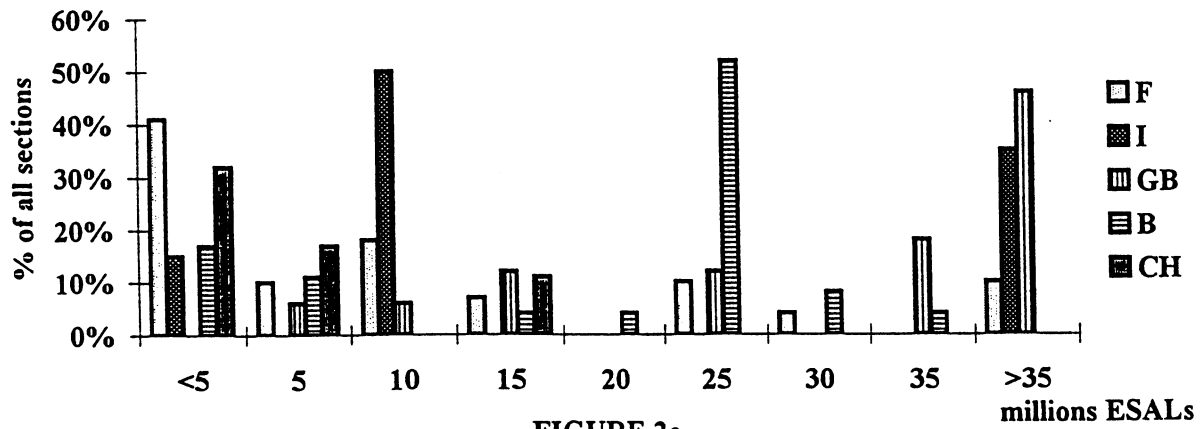


FIGURE 2c

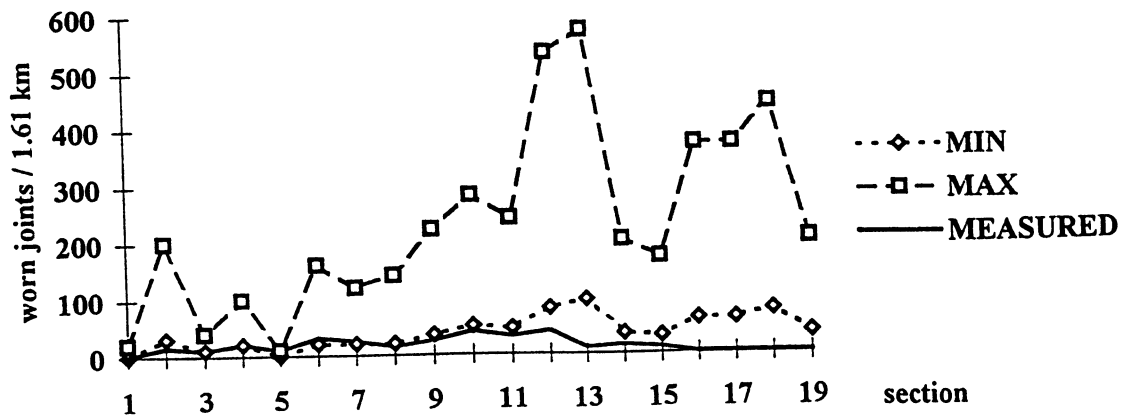


FIGURE 3

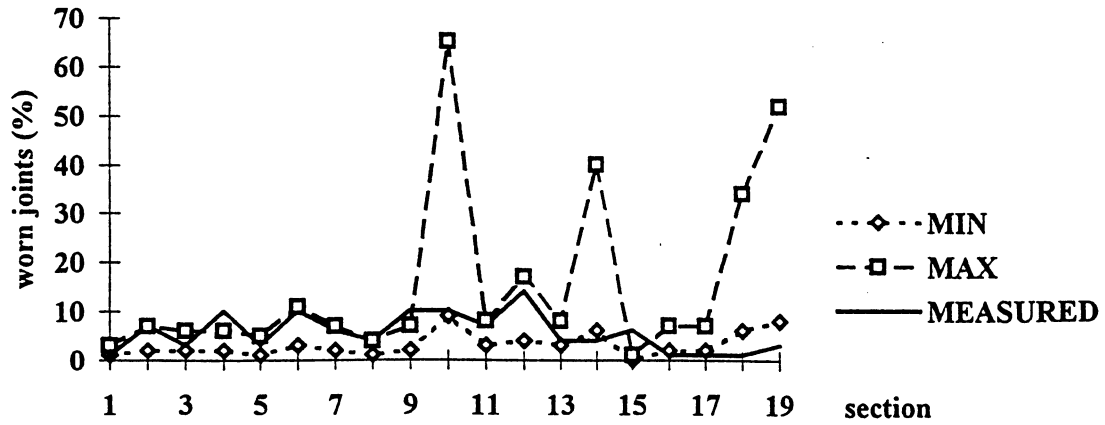


FIGURE 4

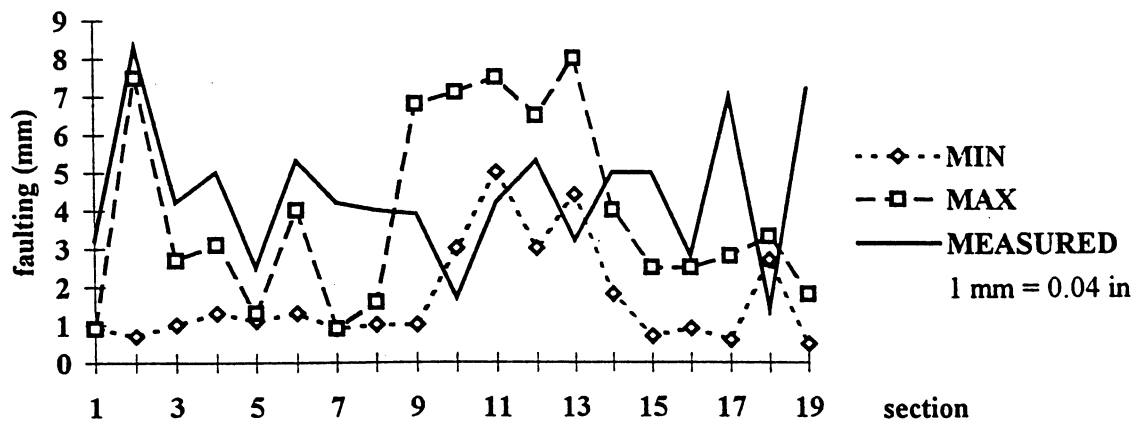


FIGURE 5

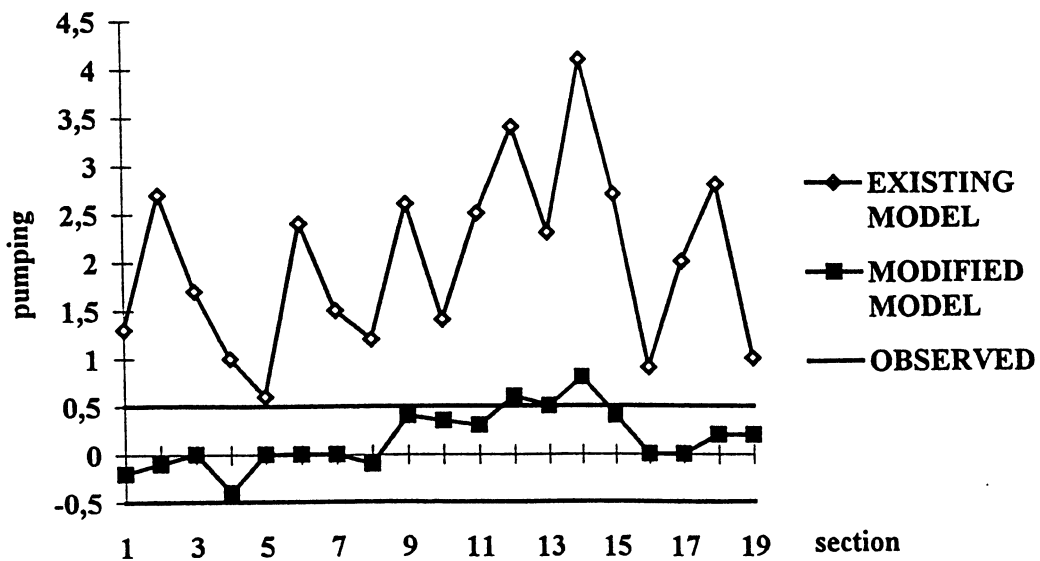


FIGURE 6

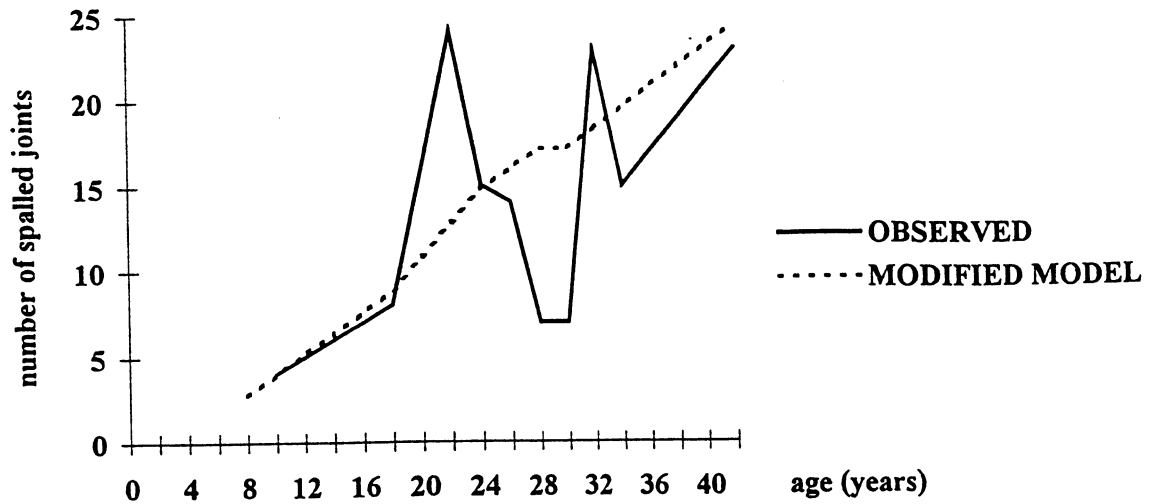


FIGURE 7

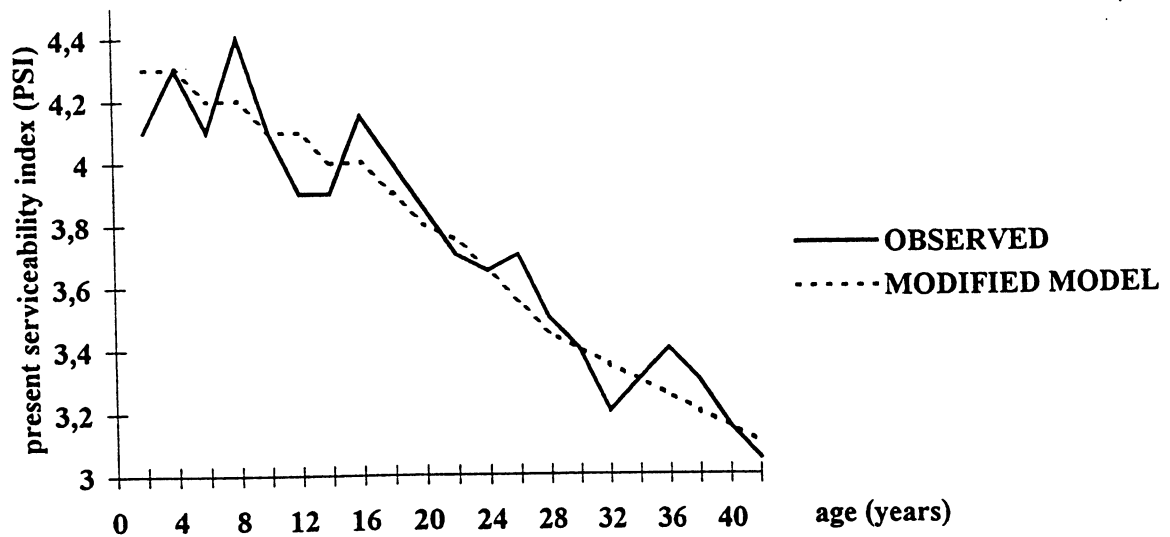


FIGURE 8

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