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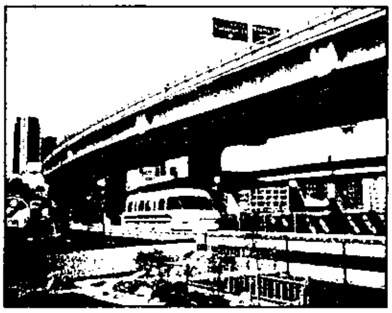

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Discussions and Closures

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DISCUSSIONS AND CLOSURES

Discussion of "Development of Fatigue Cracking Prediction Models Using Long-Term Pavement Performance Database" by Hsiang-Wei Ker, Ying-Haur Lee, and Pei-Hwa Wu

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The fatigue mechanism of an asphalt pavement is a complex phenomenon due to its materials' behavior, loading conditions, environment factors, etc. In the paper under discussion, some regression equations for bottom-up fatigue cracking (FC) were presented using long-term pavement performance (LTPP) database. Rajbongshi and Das (2009) also developed the field fatigue equation systematically using the LTPP database, and validated its goodness of fit. The paper also studied the goodness of fit of different FC models. I have some observations in context of this paper, and given in the following paragraphs. Variables are used as defined in the paper.

While comparing the goodness of fit of various FC models, the existing models [Eqs. (4) and (5) of the paper] were shown in Figs. 2(a) and 2(b), and the proposed models [Eqs. (6) or (7) and (12) of the paper] were shown in Figs. 2(c) and 2(d). The data points used for Figs. 2(c) and 2(d) were the same data considered while developing the respective regression model, whereas this was not the case for Figs. 2(a) and 2(b). This may be the cause for significant difference of goodness of fit between the existing models and proposed models. Further, from Eq. (5) one can calculate FC=0.046% for $D_f=1$, FC=0.772% for $D_f=10$, or FC < 0.8% for any value of D_f. These FC values are excessively small or even impossible, as presented along the y-axis of Fig. 2(a). Thus, Fig. 2 provides biased information and may confuse readers. FC progression in asphalt pavement being complex, there is a need to validate the performances of observation-based regression equations [Eqs. (7)–(12) of the paper] using another set of data.

Eqs. (7)–(12) of the paper accommodate various parameters as independent variables, namely age, kesal, epsilon.t, precip, temp, ft, etc. Some of them are varied within the pavement section and some are varied from section to section. It is not clear whether epsilon.t of the pavement section is the initial strain value, or the strain is considered to vary with load repetitions/age (i.e., vary within the section) due to material degradation. Also, the parameter kesal (i.e., mean yearly load repetitions in kESAL) is equal to the total load repetitions applied divided by the age (in years). Hence, the condition of independency among age, kesal, and epsilon.t of the section becomes questionable while developing the FC models. In case they are dependent, it is necessary to consider their dependency (or covariance) to justify the FC predictions. Further, it is confusing why the FC is independent of load repetitions (or kesal) as given in Eqs. (9) and (10) of the paper. Eq. (10) does not include the parameter age also. In fact, FC is caused by accumulated traffic loads with pavement age.

Bottom-up FC as percentage of lane area observed at the pavement surface in the form of alligator cracks. After certain load repetitions, cracks initiate at the bottom of the asphalt layer and subsequently propagate toward the surface. That is why the tensile strain at the bottom of asphalt layer (i.e., ε_t or epsilon.t) is considered to be the primary cause of FC. The progression of the bottom-up FC has been presented in Fig. 1. It may be mentioned here that the FC (in %) value will be zero until the cracks reach the top of the asphalt layer. Therefore, FC=0% (1) does not provide any meaningful information about the load repetitions passed (or damage factor D_f), and (2) is not of interest for evaluation of pavement failure or fatigue life (N_f). As such, the data points with FC=0% shall be ignored while expressing the FC as function of load repetition and/or pavement age. However, it is seen that most of the data points used in the paper represent 0% FC value (refer to Figs. 1 and 2 of the paper). At the same time, it is also seen that the developed equations [Eqs. (7)–(12) of the paper] do not exist at FC=0%. A better correlation could have been established if 0% FC data would not have been included. This can be observed from Figs. 2(c) and 2(d) of the paper, where it is seen that the developed regression equations (with $R^2 < 0.5$) underestimate the FC value above 0% FC (for almost all data points considered during development). Also, to justify the performance of any regression equation with many parameters as independent variable [say, Eq. (12) of the paper], considerably large data size is necessary to consider while developing the equation. Moreover, very few numbers of field data can be seen from Fig. 1 or 2 of the paper with FC > 0%. Insufficient field data and complex FC progression with age are the primary reasons for which a field fatigue equation at a pre-specific level of FC is obtained through calibration of laboratory equation, as well as with less number(s) of independent variable. Also, the parameter C in Eq. (3) of the paper is defined as the laboratory to field adjustment factor. In fact, C is the correction factor for asphalt mix volumetric, which was introduced by the Asphalt Institute, irrespective of laboratory or field fatigue equation.

The developed models, as presented in the paper, may confuse readers/pavement designers. Let us consider Eq. (7) of the paper with $R^2=0.33$. For a known value of input parameters for a given pavement section, it may be written as

$$FC = C_1 \times e^{0.121 \times \text{age}} \tag{1}$$

where

$$C_1 = e^{-7.455+0.00168 \times \text{kesal}+0.00269 \times \text{precip}+0.04738 \times \text{temp}+12319.5 \times \text{epsilon.t}+0.0133 \times \text{ft}}$$

This equation indicates that FC of the pavement section varies with age. It could have been better if FC of the section would have been expressed as a function of total load repetitions instead of age, which could take into account traffic growth/variation

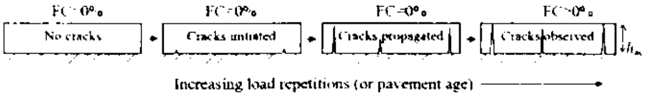

Fig. 1. Progression of bottom-up FC in asphalt pavement

with age. The year-wise traffic repetitions for various sections (in kESAL) are available from the LTPP database. Further, from Eq. (1) it is seen that FC >0% even if age=0 years. In fact, it is believed that most of the pavement age (or load repetitions) of an in-service pavement would pass before the bottom-up cracks reflect at the surface (i.e., FC=0%).

As a whole, this work is a good attempt to handle the nonlinear fatigue damage progression of different asphalt pavements with time. However, the performances of the developed fatigue cracking models are questionable for evaluation of pavement failure. There is a need to incorporate certain conceptual issues that can predict the fatigue cracking more accurately. Further, the paper requires certain clarifications to avoid confusion to the readers.

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Indeed, fatigue mechanism of asphalt pavement is a very complicated phenomenon. Every effort has been made to preserve as many observations from the LTPP database as possible. With the help of graphical representation, fatigue cracking data were plotted against surveyed years for each section in the database with additional information displayed. For example, a plot as shown in Fig. 1 was used to examine the distress trends to identify possible data errors. The upper left-hand-corner plot labeled as "37/1028, h1=9 cm, temp=16, kesal=172.4, trfopen=1982" indicated that a pavement located in North Carolina (state code=37), SHRP identification number (SHRP id)=1028, thickness of AC layer (h1)=9 cm, mean annual temperature (temp)=16°C, mean yearly ESAL (kesal)=172.4 (thousands), and traffic open year =1982, respectively. Each section was carefully examined. Two additional codes were assigned to each section to indicate the findings of the examination; that is, whether the fatigue cracking is reasonable according to the distress history, or which year of data are questionable and could be deleted if necessary. Data correction and preparation were made in a way that could be easily traced back. By doing so, different subsets of the final database providing more reliable data might be analyzed for different purposes. Of the 185 observations (40 sections), 9 data points were identified as possibly having some maintenance or rehabilitation activities although not recorded in the database. Thus, the remaining 176 data points were used in the subsequent analysis.

Some basic descriptive statistics regarding the data range, its variation, and the number of missing values for each individual variable are given in Table 1, where age stands for pavement age (years); cesal is the cumulative ESALs (millions); kesal is the yearly ESALs (thousands); h1 and h2 are the thickness of the AC surface layer and base layer (cm), respectively; e1 is the stiffness of the AC layer (MPa); epsilon.t (ε_t) is critical tensile strain; ft is yearly freeze-thaw cycle; temp is mean annual temperature (°C); precip is mean annual precipitation (mm); act.fc is actual fatigue cracking (%). A histogram only displays a rough and crude shape of the distribution of data. To have a smoother look, a continuous curve of the nonparametric estimate of the probability density may also be obtained. A normal probability plot or a quantile-quantile plot can be used to have a quick visual check on the assumption of normal distribution. If the distribution is close to normal, the plot will show approximately a straight-line relationship (Venables and Ripley 2002; Insightful 2003). As shown in Fig. 2, the actual fatigue cracking (act.fc) has a relatively skewed distribution.

A correlation matrix of these variables is given in Table 2. In addition, trimmed correlation matrices show the variable correlations after a certain portion of influential data points or possible outliers are eliminated such that more reliable indices of the correlations are obtained. For example, if 3% of the data were eliminated and the resulting trimmed correlation matrix is obtained, the relationships of actual fatigue cracking versus cesal and kesal change from negatively correlated (or no correlation) to positively correlated as shown in Table 3. The effect of the thickness of the AC surface layer (h1) changes from negatively correlated (−0.12) to negligible (−0.029). Pavement age, critical tensile strain, and mean annual precipitation still remain positively correlated with the actual fatigue cracking. Since the difference between the resulting traditional correlation matrix and trimmed correlation matrix was noticeable, special attentions were needed in analyzing this set of data. A scatter plot matrix can graphically represent their relationships and scatters. Applying a data smoothing technique (lowess) on the same scatter plot matrix, the pairwise relationships as shown in Fig. 3 may become clearer and possible data errors may also be identified (Venables and Ripley 2002; Insightful 2003).

Of the 176 data points (containing GPS-1 and GPS-2 data), only LTPP GPS-1 data was shown in Fig. 2(a) in the original paper. However, only 31 LTPP sections containing 140 data points were used in preparing Fig. 2(b) in the original paper while investigating the goodness of fit of the MEPDG models (Wu 2006, pp. 133–134). The FC predictions of the other 36 data points could not be obtained due to missing values of the additional required variables. The entire set of data was used in Fig. 2(c) and Fig. 2(d) in the original paper. Furthermore, using Eq. (5) for fatigue cracking prediction might result in excessive small FC (%) values as shown in Fig. 2(a) in the original paper. Perhaps Eq. (5) was not intended for such analysis.

To estimate the critical tensile strain (ε_t) of the AC surface layer, a systematic approach was used and implemented in a Visual Basic software package to automatically read in the pave-

Table 1. Univariate Statistics

Name	N	MEAN	STD_DEV	SUM	MIN	MAX
age	176	14.4317	5.6884	2.54E+03	4.0521	30.2621
cesal	176	1.8807	3.1713	3.31E+02	0.1481	27.1239
kesal	176	127.2544	181.4683	2.24E+04	14.2143	1,559.8800
h1	176	12.2136	6.6022	2.15E+03	3.5560	30.4800
h2	176	23.5700	14.3070	4.15E+03	0.0000	57.9120
e1	176	5,565.0727	2,156.8489	9.80E+05	1,489.9970	11,237.5004
epsilon.t	176	0.0002	0.0001	3.17E−02	0.0000	0.0003
ft	176	82.0481	48.2164	1.44E+04	3.0882	156.6522
temp	176	12.9434	5.8603	2.28E+03	3.9826	22.7559
precip	176	817.3577	440.9776	1.44E+05	72.6306	1,526.0435
act.fc	176	4.4500	10.6897	7.83E+02	0.0000	65.3549

Table 2. Correlation Matrix

Name	age	cesal	kesal	h1	h2	e1	epsilon.t	ft	temp	precip	act.fc
age	1.00	0.23	0.04	0.14	−0.20	0.02	−0.02	−0.20	0.00	0.00	0.11
cesal	0.23	1.00	0.96	0.33	−0.12	−0.14	−0.16	−0.26	0.25	−0.07	−0.01
kesal	0.04	0.96	1.00	0.35	−0.10	−0.11	−0.24	−0.27	0.29	−0.04	−0.04
h1	0.14	0.33	0.35	1.00	−0.21	−0.18	−0.55	−0.09	−0.12	0.21	−0.12
h2	−0.20	−0.12	−0.10	−0.21	1.00	0.05	0.00	0.11	0.03	−0.22	−0.17
e1	0.02	−0.14	−0.11	−0.18	0.05	1.00	−0.13	−0.42	0.45	0.15	−0.15
epsilon.t	−0.02	−0.16	−0.24	−0.55	0.00	−0.13	1.00	0.12	0.01	−0.09	0.30
ft	−0.20	−0.26	−0.27	−0.09	0.11	−0.42	0.12	1.00	−0.84	−0.53	−0.11
temp	0.00	0.25	0.29	−0.12	0.03	0.45	0.01	−0.84	1.00	0.37	0.10
precip	0.00	−0.07	−0.04	0.21	−0.22	0.15	−0.09	−0.53	0.37	1.00	0.33
act.fc	0.11	−0.01	−0.04	−0.12	−0.17	−0.15	0.30	−0.11	0.10	0.33	1.00

Table 3. Trimmed Correlation Matrix (Deleted 3% of the Data)

	age	cesal	kesal	h1	h2	e1	epsilon.t	ft	temp	precip	act.fc
age	1.00	0.38	−0.01	0.18	−0.15	0.06	−0.02	−0.19	−0.01	0.03	0.17
cesal	0.38	1.00	0.91	0.50	−0.01	−0.22	−0.30	−0.22	0.15	0.20	0.32
kesal	−0.01	0.91	1.00	0.46	0.01	−0.18	−0.39	−0.30	0.29	0.18	0.27
h1	0.18	0.50	0.46	1.00	−0.15	−0.16	−0.67	−0.11	−0.12	0.21	−0.03
h2	−0.15	−0.01	0.01	−0.15	1.00	0.12	−0.06	0.03	0.06	−0.18	−0.19
e1	0.06	−0.22	−0.18	−0.16	0.12	1.00	−0.21	−0.46	0.51	0.05	−0.16
epsilon.t	−0.02	−0.30	−0.39	−0.67	−0.06	−0.21	1.00	0.12	0.01	−0.12	0.19
ft	−0.19	−0.22	−0.30	−0.11	0.03	−0.46	0.12	1.00	−0.86	−0.63	−0.11
temp	−0.01	0.15	0.29	−0.12	0.06	0.51	0.01	−0.86	1.00	0.48	0.08
precip	0.03	0.20	0.18	0.21	−0.18	0.05	−0.12	−0.63	0.48	1.00	0.37
act.fc	0.17	0.32	0.27	−0.03	−0.19	−0.16	0.19	−0.11	0.08	0.37	1.00

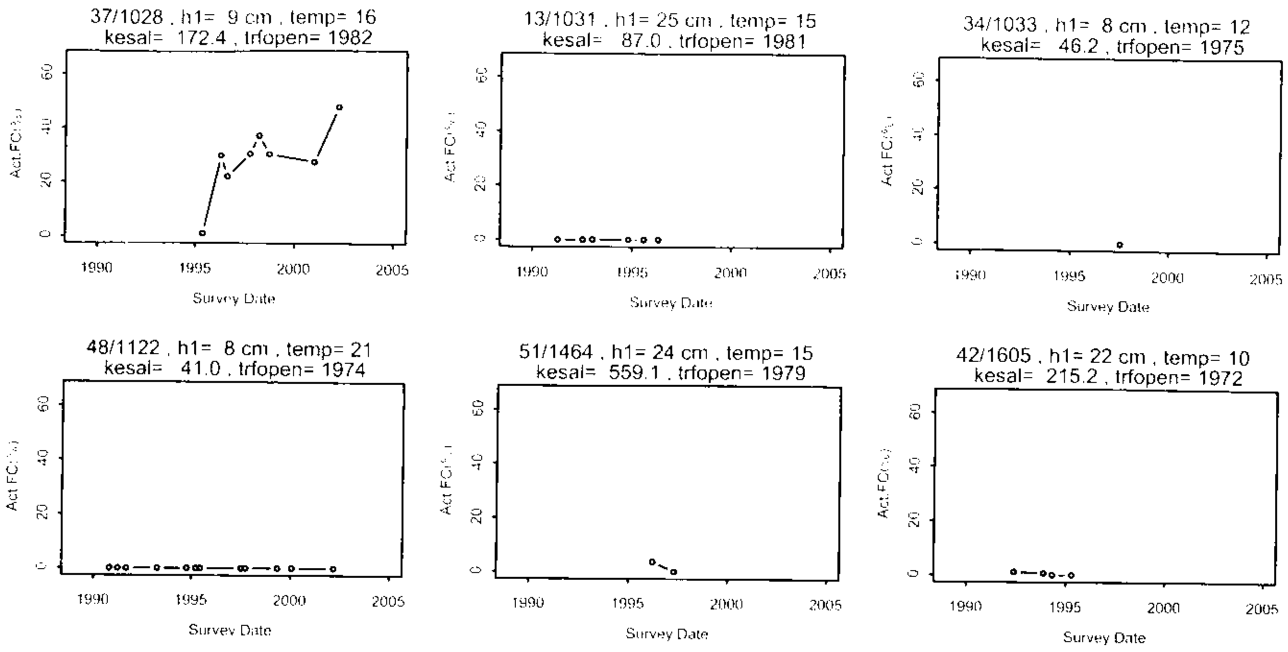

Fig. 1. Sample fatigue cracking history of the database

ment inventory data from the summary table, generate the BISAR input files, conduct the batch runs, as well as summarize the results (Wu 2006). The static (or laboratory tested) elastic modulus data recorded in the IMS testing module and a single wheel load of 40 kN (9,000 lbs) with a tire pressure of 0.482 MPa (70 psi) were used for the analysis. Special efforts have been made to keep as many dominating variables with reasonable physical meanings in the preliminary and proposed statistical models [i.e., Eqs. (6)–(12)]. Based on the available data, the load repetition (or kesal) or pavement age has to be eliminated from Eqs. (9) and (10) due to insignificant and/or inappropriate parameters (Wu 2006). It is not uncommon that statistical regression models do not always agree with engineering expectations using limited field data.

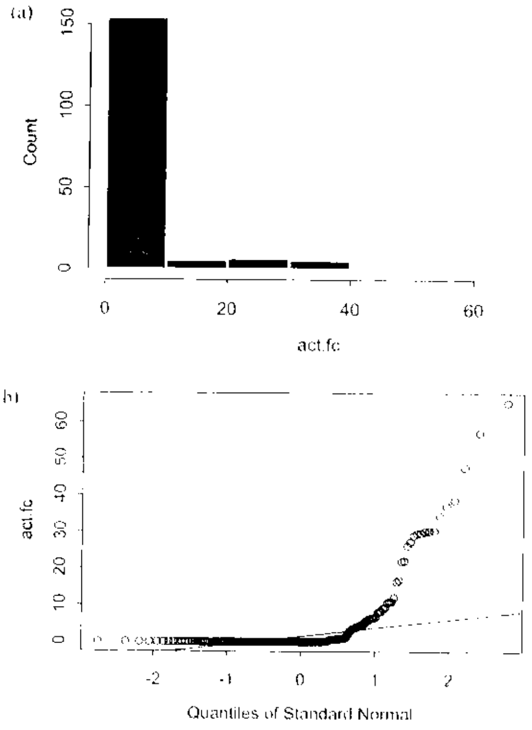

Fig. 2. Distribution of fatigue cracking: (a) a histogram; (b) a normal probability plot

The writers do not agree with the argument that FC=0% does not provide any meaningful information and/or is not of interest for evaluation of pavement failure. Due to the data collection nature of fatigue cracking, fatigue cracking could be treated as rate data or as a continuous variable. There is no reason to manually eliminate such important information that knowing fatigue cracking is still invisible under certain conditions. Elimination of FC=0% data from the analysis will result in tremendous bias to the research findings (i.e., overestimation). In fact, preserving as many field observations as possible has been adopted as a common practice for the performance analysis for decades (ARA 2004, Appendix II-1; Lee 1993; Simpson et al. 1993).

In summary, this paper intends to investigate the goodness of fit of the existing models for fatigue cracking prediction. An alternative systematic statistical and engineering approach was used in the subsequent analysis. After many trials in eliminating insignificant and inappropriate parameters, tentative prediction models were proposed. The proposed models appeared to reasonably agree with the available data, although further enhancements are possible and recommended. In addition, having some basic statistical knowledge on regression analysis and hypothesis testing may help to ease the misunderstanding and confusions as mentioned in the discussion.

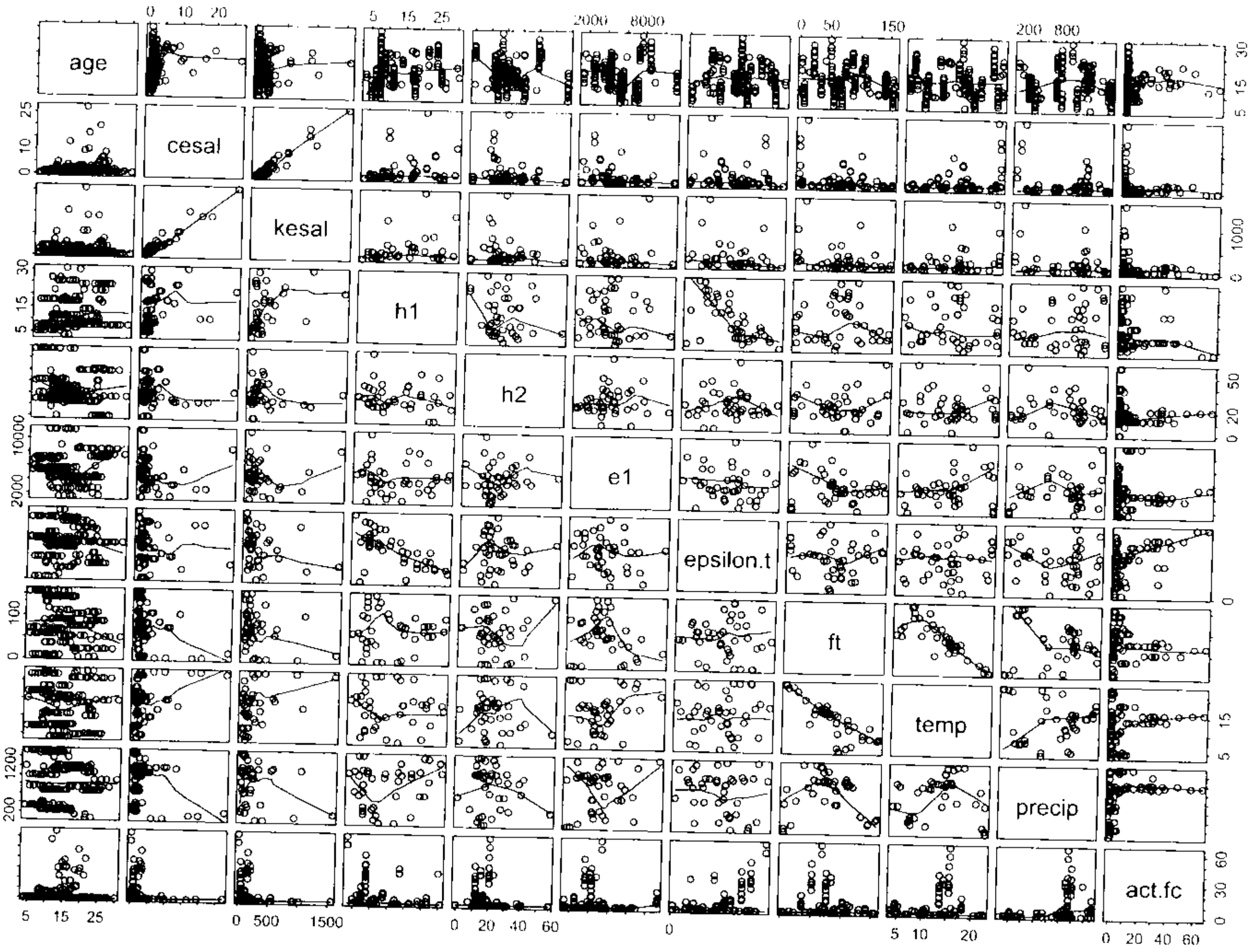

Fig. 3. Using scatter plot smoother (lowess) on the scatter plot matrix

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