THE SEPARATE EFFECTS OF TRAFFIC LOADING AND ENVIRONMENT ON RUTTING AND CRACKING TRENDS OF ASPHALT PAVEMENTS

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Abstract. Road pavements deteriorate with traffic loading and environment but the separate effects of these factors are not yet well defined especially with age or environment. This paper aims at finding the separate effects of these two factors on asphalt pavement rutting and cracking. It is believed that this will lead to better modeling of pavement deterioration by clearly understanding and treating the two factors as separate entities. A methodology was devised to separate the two effects, in which pavement age is used to represent the cyclic effect of environmental forces, and analysis was carried out. Results show how each of these factors influence pavement rutting and cracking and provide a further understanding of the influence of some of pavement parameters on pavement rutting.

Keywords. Traffic loading, Environment, Rutting, Cracking, Pavement deterioration.

BACKGROUND AND AIM

Due to the importance of roads as one of the major means of transport, there has been an increase in the number of roads constructed worldwide in the past decades. Management of roads, including providing routine maintenance, rehabilitation, or reconstruction, has therefore become more important. Since maintenance planning depends upon the ability of the highway agency to accurately predict future pavement condition, it is very important to be able to specify and estimate an accurate deterioration model.

Many people in the field of pavement performance have stated that one of the largest deficiencies is the absence of an accurate understanding of pavement distress progression in relation to causal factors such as traffic loading, environment, and others. Many researchers have reported that deterioration prediction models have poor fit to data and do not accurately predict future conditions. Some researchers have attributed this to the incomplete specification due to the difficulties associated with the measurement of environmental effects and other intangibles such as quality of initial construction. Others have sighted the influence of maintenance policy. Ramaswamy and Ben-Akiva (1990) observed that the poor performance of even the more realistic specifications indicate that there is a problem with the traditional approaches used to model the deterioration of highway pavements. Although it is acknowledged that pavements deteriorate with traffic, time, and environment, the separate or interacting effects of these components are not clearly defined at the present time, especially with regard to age or environment (AASHTO 1993). This research was aimed at studying how pavement rutting and cracking develop with traffic loading and environment as separate effects. It is hoped that understanding the distinct and separate effects of traffic loading and environment will improve the modeling of pavement deterioration as a combined process of these distinct effects.

The AASHO Road Test (1962) gave an insight on

the effect of traffic loading but since its sections survived for only one or two years, the test results do not indicate the long-term effect of environmental factors. Its report encouraged research into the effects of environment and into the mechanical and physical laws involved in pavement performance. It further recommended that immediate attention be given to means for extending the empirical models developed to include additional important parameters. This research was initiated in line with this recommendation. Furthermore, results obtained here should help in understanding the much required mechanical mechanism.

Pavement rutting and cracking are two main distresses that reflect on the pavement structural strength and are mainly used in determining pavement rehabilitation. Significant rutting lead to major structural failure of the pavement, causes discomfort to the traveling public, and is a potential hazard due to the likelihood for hydroplaning caused by water pooled in wheel track depressions. Cracks reduce the bearing capacity of the pavement and allow water ingress which further weakens the pavement and rapidly quickens its deterioration.

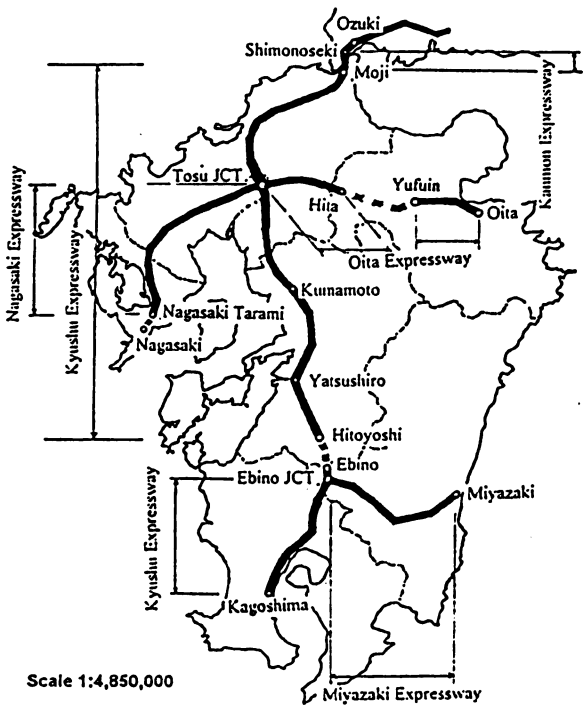


Fig.1 Kyushu Expressways

GENERAL APPROACH

Environmental Factor. There are two main environmental factors, temperature and rainfall, with regard to pavement performance (AASHTO 1993). Because of exposure to climatic cycles, the real-life pavements suffer deterioration over a period of time, even under low traffic volumes. In this research, pavement age is used to represent the cyclic effect of environmental forces. For age to be used as such, all the data have to be of pavements from areas with same climatic conditions. An analysis of means for temperature and precipitation carried out for 5 regions in Kyushu, Japan, an area whose data were used, showed no significant climatic differences. The region has, on average, a minimum temperature of 4.5 °C, a maximum temperature of 34.0 °C, a mean daily min. temperature of 11.0 °C, a mean daily max. temperature of 20.5 °C, and an annual rainfall of 2055 mm. From soil condition records, the groundwater conditions were assumed to be the same. The analysis here is therefore aimed at finding the progression of rutting and cracking due to environmental effects rather than the effect of different climatic or environmental conditions. Fig. 1 shows expressways in Kyushu island, about 570 kms in total length, whose data were used.

Pavement Structural Strength. The Japanese method of pavement design is based on the AASHO Road Test concept. The required equivalent pavement thickness, T_A, is calculated using design subgrade CBR and cumulative 10 ton equivalent axle loads (EAL) as shown in Fig. 2. The equivalent pavement thickness is then used to calculate individual layer thicknesses using layer coefficients (JH 1993). All the expressway pavements whose data were used had a 100 mm

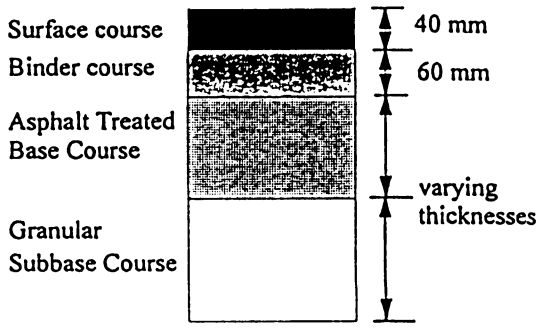


Fig. 3 Typical Pavement Cross-section

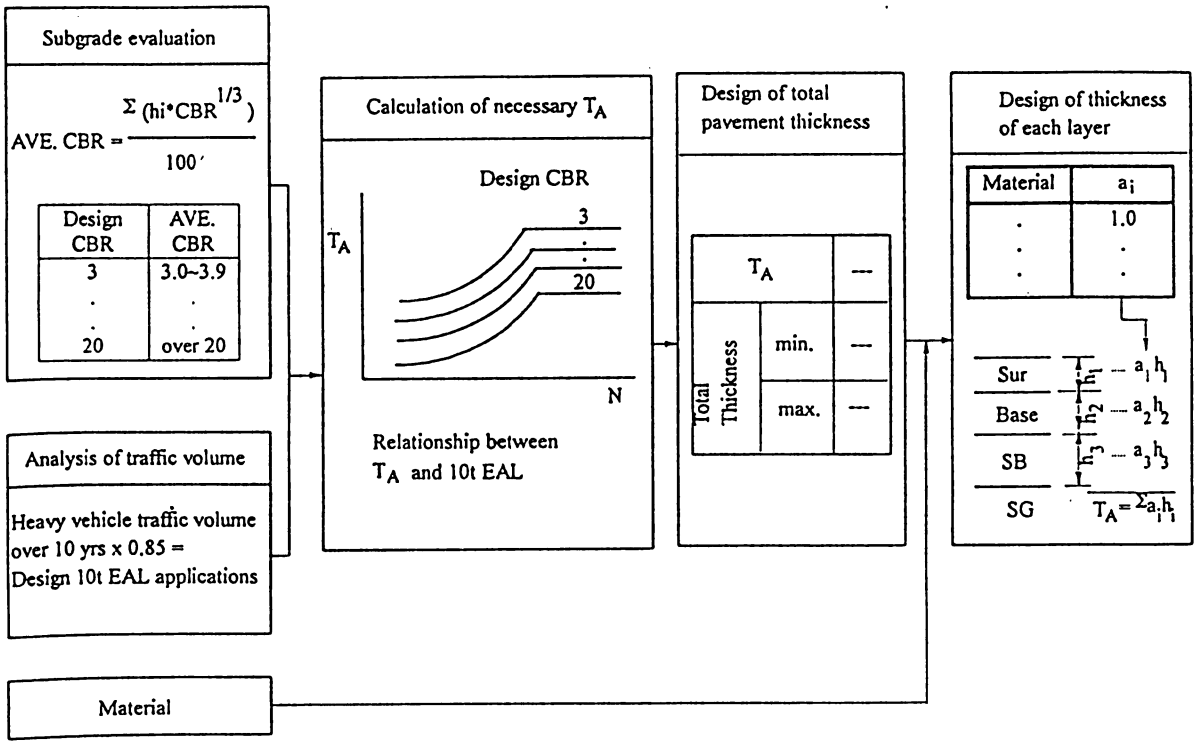


Fig. 2 Japanese Pavement Design Procedure

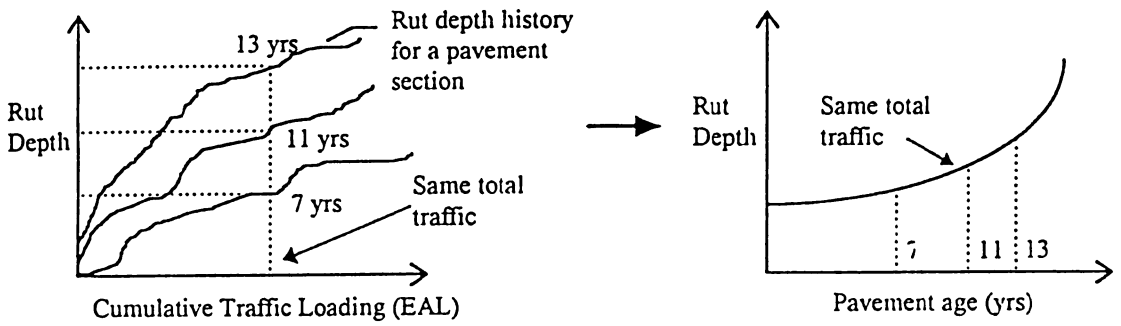


Fig. 4 Illustration of Formation of a Group of Data e.g. for environmental effect analysis

Table 1: Pavement Structural Groups

GROUP		T_A (cm)	CBR
A	Range	21.0 - 24.5	8.0 - 10.0
	Rep. value	22.75	9.0
B	Range	21.0 - 24.5	10.5 - 15.0
	Rep. value	22.75	12.75
C	Range	24.5 - 27.0	7.0 - 10.0
	Rep. value	25.75	8.5
D	Range	28.0 - 31.0	4.0 - 8.0
	Rep. value	29.5	6.0

surface-and-binder course, an asphalt-treated base, and a granular subbase as shown in Fig. 3. Different thicknesses of base and subbase layers together with different subgrade CBR values resulted in pavements with different structural strengths. Granular material for the subbase included decomposed weathered granite, sandstone, etc. The top 1 m of the subgrade consisted mostly of burrowed material ranging from decomposed granite, crushed stone, mixed sand-gravel, to clay.

To eliminate the influence of pavement structural strength, analysis had to be done on data from road sections with similar structural strengths. This led to the division of all pavements into 4 groups of equal structural strengths according to T_A and CBR as shown in Table 1. Since historical data were used, formation of the groups was highly dictated by the availability of data. However, care was taken to have enough data in each group to enable adequate analysis. Groups were formed within ranges that would present a difference from other groups, and at the same time not too wide to allow much difference in strength of the individual pavements within.

Separation of Traffic Loading and Environmental Effects. To obtain environmental effects only, the effect of traffic loading had to be removed. This was achieved by grouping pavements of different ages into groups of same total cumulative traffic loading (Equivalent Single Axle Loads; EAL) and observing trends within the groups. The age variable could then represent the pure environmental effect. In a similar manner, fixing age by grouping pavements with same age but different EAL gave the pure effect of traffic loading. Fig. 4 illustrates the formation of same EAL group of data for the analysis of environmental effect.

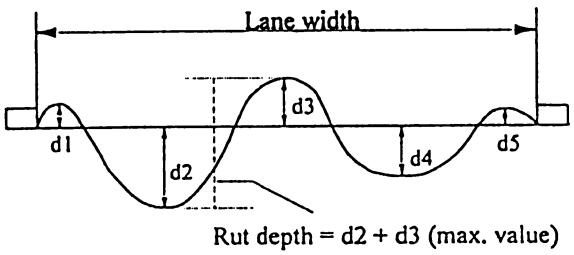


Fig. 5 Rut Depth Measurement

DESCRIPTION OF DATA

There were pavements of up to 18 years old and 10 tf cumulative EAL ranged from 30,000 to 13,000,000 providing a wide range for analysis. However, there were more data in the case of rutting than cracking because more surveys were conducted on rutting. Table 2 shows road sections of all the expressways whose data were used, their time of construction, the survey time and their ages at the time. The number of data that could be used was highly reduced due to the necessity of using condition data of pavements before rehabilitation to avoid trend distortion.

Rutting Data. Accurate measurement of pavement distress is very important, without which a PMS output would become unreliable. The rut measurement method employed here is widely used by Japan Highway Public Corporation (JH), which oversees all the expressways in Japan. Rut depths are automatically measured by an automobile and are decided as shown in Fig. 5, summarizing an average for each 100 m section.

Screening of rutting data posed a great challenge. As was observed in the AASHO Road Test, which measured rut depth serially, rutting does not increase monotonically although in overall it eventually increases with loading. Fig. 6 shows a typical case of rut depth vs EAL in the AASHO Road Test. In such shifting tendencies of increasing and decreasing rut depths, a reduced rut depth in one or two years could not be interpreted as resulting from rehabilitation. Only in cases where there was a big reduction in rut depth and no rebound in subsequent years was the data left out. Rehabilitation (not in record) or a recording error was assumed.

Grouping and screening of data reduced the amount of available data to around 9,000 data points for either analysis. Overlapping in EAL ranges (see Table 4 later) and therefore reuse of same data was employed to increase the number of cases for environmental effect analysis. Some EAL ranges are

Table 2: Road Sections

HIGHWAY	ROAD SECTION	L	CONST	AGE AT INDICATED TIME OF SURVEY				
		(km)	MM/YY	10/1988	10/1990	10/1991	08/1992	08/1993
KANMONKYO	SHIMONOSEKI ~ MOJIKO	4.3	11/1973	15.0	17.0	18.0	19.0	20.0
	MOJIKO ~ MOJI	5.1						
KYUSHU-A	MOJI ~ KOKURA HIGASHI	13.3	03/1984	4.5	6.5	7.5	8.5	9.5
	KOKURA HIGASHI ~ KOKURA MINAMI	6.9	03/1988	0.5	2.5	3.5	4.5	5.5
	KOKURA MINAMI ~ YAHATA	11.1						
	YAHATA ~ WAKAMIYA	13.9	03/1979	9.5	11.5	12.5	13.5	14.5
	WAKAMIYA ~ KOGA	12.5	07/1977	11.0	13.0	14.0	15.0	16.0
	KOGA ~ FUKUOKA	10.6	03/1975	13.5	15.5	16.5	17.5	18.5
	FUKUOKA ~ DAZAIFU	11.7						
	DAZAIFU ~ YOSU(J)	16.0						
	YOSU(J) ~ KURUME	9.4	11/1973	15.0	17.0	18.0	19.0	20.0
	KURUME ~ YAME	13.0						
	YAME ~ NANKAN	16.6						
	NANKAN ~ KIKUSUI	11.6	10/1972	16.0	18.0	19.0	20.0	21.0
	KIKUSUI ~ UEKI	10.7						
	UEKI ~ KUMAMOTO	13.9	06/1971	17.5	19.5	20.5	21.0	22.0
	KUMAMOTO ~ MIFUNE	11.9	11/1976	12.0	14.0	15.0	16.0	17.0
	MIFUNE ~ MATSUBASE	12.0	12/1978	10.0	12.0	13.0	14.0	15.0
	MATSUBASE ~ YATSUSHIRO	18.4	03/1980	8.5	10.5	11.5	12.5	13.5
	YATSUSHIRO ~ HITOYOSHI	42.7	12/1989		1.0	2.0	3.0	4.0
KYUSHU-B	EBINO ~ EBINO(J)	2.0	10/1981	7.0	9.0	10.0	11.0	12.0
	EBINO(J) ~ KURINO	13.7						
	KURINO ~ YOKOKAWA	6.0	03/1980	8.5	10.5	11.5	12.5	13.5
	YOKOKAWA ~ MIZOBE	13.8						
	MIZOBE ~ KAJIKI	7.7	11/1976	12.0	14.0	15.0	16.0	17.0
	KAJIKI ~ AIRA	8.7	12/1973	15.0	17.0	18.0	19.0	20.0
	AIRA ~ SATSUMA YOSHIDA	8.6						
	SATSUMA YOSHIDA ~ KAGOSHIMA KITA	6.9	11/1977	11.0	13.0	14.0	15.0	16.0
	KAGOSHIMA KITA ~ KAGOSHIMA	4.4	03/1988	0.5	2.5	3.5	4.5	5.5
MIYAZAKI	EBINO(J) ~ KOBAYASHI	15.9	03/1976	12.5	14.5	15.5	16.5	17.5
	KOBAYASHI ~ TAKAHARA	10.6						
	TAKAHARA ~ MIYAKONOJO	20.4	03/1981	7.5	9.5	10.5	11.5	12.5
	MIYAKONOJO ~ TANO	21.1	10/1981	7.0	9.0	10.0	11.0	12.0
	TANO ~ MIYAZAKI	12.5						
NAGASAKI	HIGASHI SEBURI ~ SAGA YAMATO	11.8	03/1985	3.5	5.5	6.5	7.5	8.5
	SAGA YAMATO ~ TAKU	15.1	03/1987	1.5	3.5	4.5	5.5	6.5
	TAKU ~ TAKEO HOPPO	11.1						
	TAKEO HOPPO ~ TAKEO(J)	11.3	01/1990		1.0	2.0	2.5	3.5
	TAKEO(J) ~ URESHINO	4.5						
	URESHINO ~ HIGASHI SONOGI	9.8						
	HIGASHI SONOGI ~ OOMURA	13.5						
	OOMURA ~ ISAHAYA	12.1	11/1982	6.0	8.0	9.0	10.0	11.0
	ISAHAYA ~ NAGASAKI TARAMI	4.9						
OITA	TOSU(J) ~ CHIKUGO OBOORI	4.9	02/1987					6.5
	CHIKUGO OBOORI ~ AMAGI	6.0						
	AMAGI ~ ASAKURA	8.1						
	ASAKURA ~ HAKI	8.5	03/1990					3.5
	HAKI ~ HITA	14.0						
	YUFUIN ~ HINODE JCT		07/1989					4.0
	HINODE JCT ~ BEPPU							

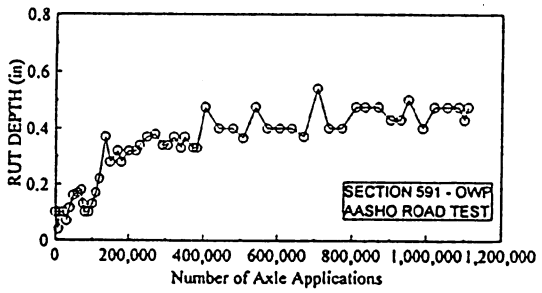


Fig. 6 Typical Rut depth vs EAL at AASHO Road Test (Thompson and Nauman 1993)

much wider in structural groups C and D because of high traffic in their roads.

Cracking Data. Until now, there is no widely accepted measure for cracking in pavements, and no international standardization has been established. Cracking data used here were obtained by JH which classifies pavement cracks into 3 types; network cracking (alligator, block, map, etc.), longitudinal cracking, and transverse cracking. The system involves surveying 100 m sections and rating cracking in ranks of 0, 1, 2, or 3. Rank 1 represents a case where a number of localized cracks begin to appear. Rank 2 represents numerous cracks starting to branch off for longitudinal cracks, covering half width for transverse cracks, and covering a wide area in the case of network cracking. Rank 3 represents a case of extensive coverage of section area with even wider cracks. Although this categorization seems to be too general, it is thought to be a more realistic way of representing something that could sometimes be considerably random. The wide ranks have therefore a better chance of portraying really difference as compared to detailed categorization.

METHOD OF ANALYSIS

For 100 m road sections with same pavement structure, same age and traffic loading at the time of survey, a representative average rut depth or crack rank was calculated after leaving out data more than two standard deviations from the mean. These mean values were then used in the analysis. Each data point in the analysis, therefore, represents a rut depth or cracking rank of more than 100 sections with similar characteristics.

The selection of analysis technique was strongly influenced by data availability and the type of results required. Since the purpose was to trace the trend of distress vs EAL in the case of traffic loading and against pavement age in the case of environmental effect, simple functions providing different forms were examined in the case of rutting analysis. Statistical and regression analysis, and rational judgement were employed. In the case of cracking, only the general trend has been observed.

RUTTING TREND

Traffic Loading Effect. Rigorous regression analysis was carried out for different forms to model the trend of effect of traffic loading on rutting. Table 3 shows coefficients of determination for each structure-age category for the regression of rut depth vs EAL. Apart from other considerations, the best form was selected based on R^2 and the power function provided the best form:

$$RUT = aEAL^b \quad (1)$$

where RUT is the rut depth in mm and EAL is 10 ton cumulative traffic axle loads.

Figs. 7(a) and (b) show the graphs for each age category for structural groups A&B and C&D respectively. The graphs show the typical effect of pure traffic loading on pavement rutting. This agrees well with the state-of-the-art understanding as was concluded at the AASHO Road Test (see Fig. 6) i.e. a lot of rutting takes place in early stages of loading and then levels off as loading increases. It can also be observed in Figures 7 that, under traffic loading, weaker pavements and older pavements experience more rutting. Higher rate of rutting in early stages of pavement loading could be explained by both the densification and shear deformation of any or all the layers in the newly constructed pavement (Sousa et al.).

To further assess the various parameters, a complete equation was developed. This was done by applying stepwise regression to values of a and b in Eq. 1 for each category against age, CBR, and T_A using group representative CBR and T_A values in Table 1. The following relations were obtained:

$$a = 949.1 - 946AGE^{0.001} \quad (1.1)$$

s=0.47537, R^2=0.49

$$b = 0.119 + 0.00757AGE - 0.00000132CBR^4 \quad (1.2)$$

s=0.03822, R^2=0.52, Adj-R^2=0.33

Table 3: Rut depth vs EAL Coefficients of Determination (R^2) for Different Forms

STR. GROUP	AGE GROUP	No.	R^2 FOR THE FUNCTION			
			ST. LINE	EXP	LOG	POWER
A	6-7	14	0.51	0.45	0.46	0.54
	8-10	14	0.10	0.09	0.10	0.15
	11-12	11	0.05	0.06	0.05	0.08
B	3-5	16	0.55	0.55	0.63	0.70
	9-11	13	0.10	0.09	0.06	0.08
	12-13	5	0.03	0.004	0.03	0.032
C	5-6	16	0.11	0.12	0.16	0.20
	9-12	12	0.70	0.75	0.76	0.88
	15-16	11	0.55	0.50	0.65	0.60
D	9-10	5	0.79	0.77	0.81	0.90
	11-12	11	0.53	0.56	0.61	0.68
	14-15	11	0.42	0.48	0.44	0.53

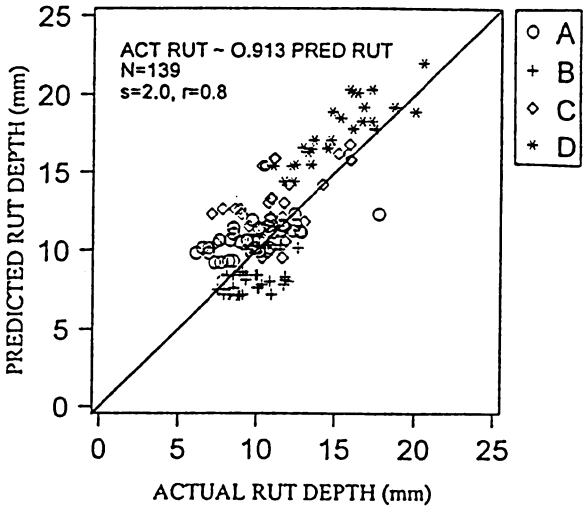


Fig. 8 Predicted vs Actual Rut depth (Eqs. 1)

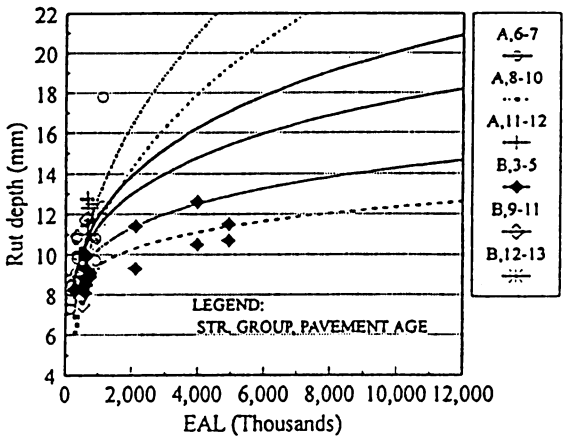


Fig. 7(a) Rut depth vs EAL Graphs Depicting Traffic Loading Effect (Groups A&B)

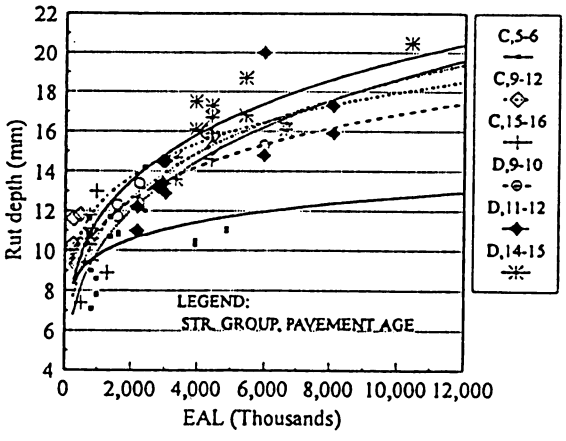


Fig. 7(b) Rut depth vs EAL Graphs Depicting Traffic Loading Effect (Groups C&D)

Both equations are significant at a confidence level of 0.05. Fig. 8 shows rut depths well predicted using the equations against actual rut depths for 139 data representing average values of pavements from all structural groups.

The coefficient *a* depends solely on pavement age while the exponent *b*, which controls the degree of curvature of the curves, increased with age and decreased with CBR. Though further analysis shows that age has more influence on *b* compared to CBR, better CBR could highly reduce the amount of pavement rutting. For instance, 5 and 15 yrs pavements with CBR=6 had rut depths of 19 and 22 mm respectively after 10 mil EAL. Under same loading, pavements of CBR=13 had 11 and 13 mm rut depths respectively. On the overall, still age had less influence compared to EAL which seemed to be the main force behind pavement rutting. The fact that T_A seemed to be of not much influence could be explained by the fact that subgrade CBR is more influential in reducing the traffic loading effect on pavement rutting in the long run. However, T_A is known to be of influence, however secondary compared with age or CBR, and the following could have contributed to its complete omission; first, there are only three different values of T_A in the 4 groups as compared to four CBR values (see Table 1). Second, looking at Table 3, there are few age groups (as compared to EAL groups in Table 4) which means less data for analysis that could have contributed to a lesser degree of accuracy.

Environmental Effect. Table 4 shows the resulting coefficients of determination for each structure-EAL category for the regression of rut depth vs pavement age. On the overall, the exponential function provided the best form:

$$RUT = ce^{dAGE} \qquad (2)$$

where *RUT* is rut depth in mm and *AGE* is pavement age in years.

Figs. 9(a) and (b) show graphs for each EAL category for structural groups A&B and C&D respectively. The graphs depict the typical trend of environmental effect on pavement rutting i.e. environmental effects increase exponentially. It can be concluded that, under similar traffic loading and structural conditions, environmental effects on rutting become severer with age which means they have a compounding effect. Other than traffic loading, the different graphs show that structural strength is a factor too with weaker pavements affected more by environmental forces. The fact that exponential form was depicted instead of a power form, which can give the same form but starts at the origin confirms the importance of the idea of initial pavement rut depth which is defined as the amount of rutting before the first year cycle.

To further examine the various parameters in detail, stepwise regression was carefully applied on values of *c* and *d* for each category against EAL, T_A, and CBR and the following expressions were obtained:

$$c = 8.132 + 0.00333EAL^{0.5} - 0.00024T_A^3 \qquad (2.1)$$

s=0.9871, R^2=0.64, Adj-R^2=0.56

$$d = 0.05579 - 0.0029CBR \qquad (2.2)$$

s=0.01011, R^2=0.34

where T_A is equivalent pavement thickness in cm. Both equations and parameters are significant at a confidence level of 0.05. Fig. 10 shows rut depths well predicted by the equations against actual rut depths representing average values of pavements from all structural groups.

The coefficient *c*, which also represents the initial pavement rut depth at age=0, increases with EAL and decreases with T_A. At zero traffic loading (EAL=0), the initial pavement rut depth depends solely on T_A, i.e.

$$RUT_{initial} = 8.13 - 0.00024T_A^3 \qquad (2.3)$$

For instance, the initial pavement rut depth is 6.2 mm for a pavement with T_A=20 cm and 1.7 mm for a pavement with T_A=30 cm. The sole dependence of initial rut depth on T_A shows that the initial rut depth is related to pavement material, thickness, and construction quality because 'as constructed' T_A values were used. *d*, which controls the degree of curvature of the curve, determines the rapidness with which rutting occurs with age.

Plots were made out of Eq. 2 to clearly portray the effects of CBR and T_A on environmental effects on pavement rutting. Fig. 11 shows the influence of CBR on typical pavements with 3 mil. EAL and T_A=24 cm. The curvature increases with less value of CBR and flattens as CBR increases showing the importance of high subgrade CBR in curbing long term environmental effects. Fig. 12 shows T_A influence on typical pavements with 3 mil. EAL and CBR=7. The degree of curvature does not change for different values of T_A, it is almost the same for all T_A values

Table 4: Rut depth vs age Coefficients of Determination (R^2) for Different Forms

STR GROUP	No.	EAL (mil) GROUP	R^2 FOR THE FUNCTION ST. LINE	EXP	LOG	POWER
A	16	0.6-0.8	0.21	0.27	0.22	0.23
	16	0.7-0.9	0.20	0.25	0.21	0.20
	5	0.8-1.0	0.16	0.17	0.13	0.13
B	5	0.4-0.6	0.40	0.44	0.41	0.44
	11	0.5-0.7	0.25	0.29	0.24	0.23
	10	0.6-0.8	0.69	0.72	0.62	0.65
C	8	0.6-0.8	0.40	0.48	0.38	0.38
	10	0.8-1.0	0.68	0.77	0.66	0.68
	10	1.4-2.4	0.34	0.38	0.39	0.37
	8	4.2-4.8	0.31	0.33	0.37	0.38
D	10	1.5-3.0	0.21	0.28	0.22	0.20
	12	2.0-3.5	0.30	0.38	0.31	0.31
	9	4.0-6.0	0.61	0.70	0.51	0.57
	9	5.5-6.5	0.29	0.39	0.26	0.26

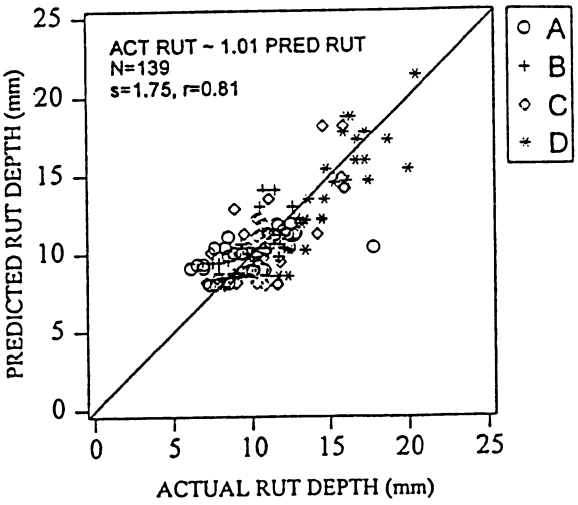


Fig. 10 Predicted vs Actual Rut depth (Eqs. 2)

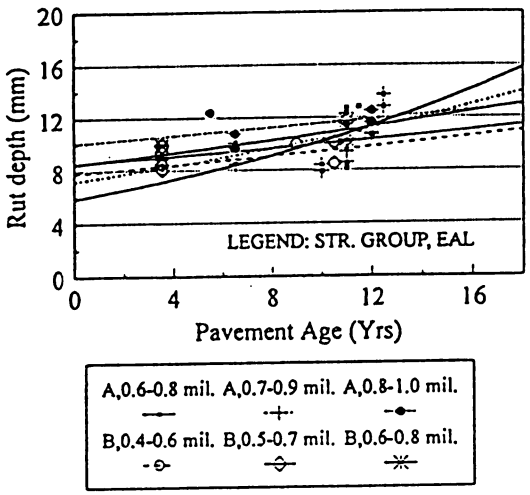


Fig. 9(a) Rut depth vs age Graphs Depicting Environmental Effect (Groups A&B)

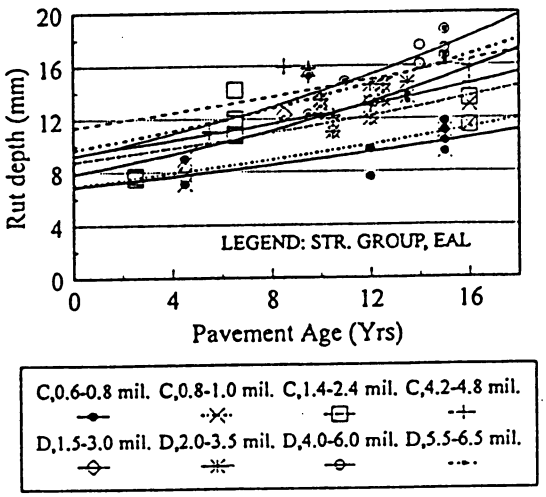


Fig. 9(b) Rut depth vs age Graphs Depicting Environmental Effect (Groups C&D)

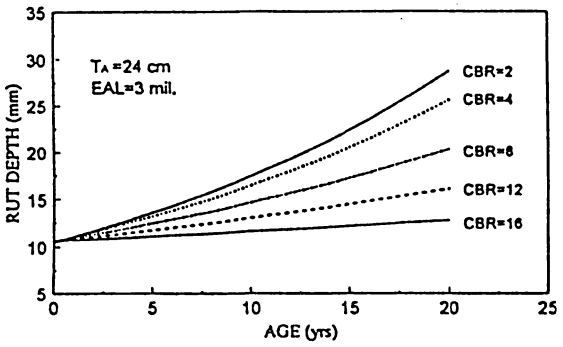


Fig. 11 Influence of Subgrade CBR on Environmental Effects on Pavement Rutting

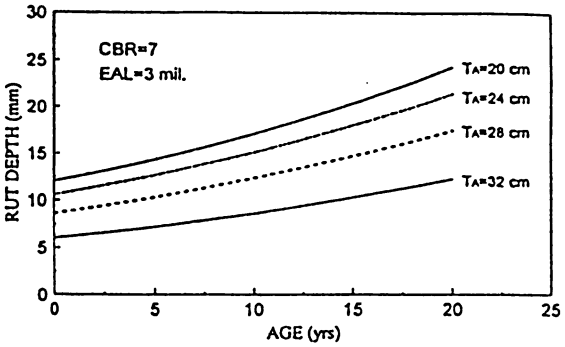


Fig. 12 Influence of T_A on Environmental Effects on Pavement Rutting

throughout the pavements life time. The difference occurs mainly at the beginning of pavement life and is almost maintained throughout the pavement life showing that T_A acts as a blanket against environmental effects.

CRACKING TREND

Due to lack of enough data to create enough categories for detailed analysis, the analysis of cracking trend is limited to general observations. As seen in Figs. 13-15, the trends were mainly observed in the case of pavements in structural groups C and D which had extensive data covering wide ranges of ages and EAL. Most data in groups A and B were clustered on same values of ages or EAL which made it difficult to observe any trend. Thus, regression lines drawn to indicate the increasing or decreasing trends appear only in cases with sufficiently wide ranges of age or EAL values. Each point is a mean crack rank representing between 100 and 500 similar pavement sections under same conditions.

However, cracking is a complex distress. As was observed by Paterson and Chesher (1986), the time at which cracking appears in bituminous pavements is influenced by both traffic and weathering and varies across pavements even under normally identical conditions.

Network Cracking. Although network cracking mainly consists of alligator cracks, this category also included map, block, and even irregular cracks. Fig. 13(a) shows that there is no clear relationship between traffic loading and network cracking. However, technical experiments have established a strong relationship between the number of axle load applications and fatigue cracking. Therefore, narrowing network cracking to mainly alligator cracking, the results can be interpreted as that the number of axle loads determines only the onset of fatigue cracking where fracture failure is thought to have occurred but does not have any defined relationship thereafter. A point to be noted here is that, a lack of relationship with traffic loading does not necessarily mean that it does not affect cracking at all. It simply shows that the difference in traffic loading does not matter, which however could also mean that there is no effect.

Fig. 13(b) shows that network cracking increases rather with age. This shows that environmental forces alone can cause network cracking. A number of studies back up this finding. As for the alligator cracks, studies such as the one by Day (1995) have shown that moisture results in a loss of effective shear strength of the subgrade which makes the pavement susceptible to alligator cracking and other distresses. For thick, full-depth AC, there are indications from research that fatigue cracking can significantly be affected by temperature (Thompson and Cation 1984). The AASHO Road Test (1962) too observed that more surface cracking occurred during periods when the pavement structure was in relatively cold state. Shrinkage due to absorption, ageing, and temperature fluctuation can cause block and random cracking. Dickinson (1984) observed that this cracking by

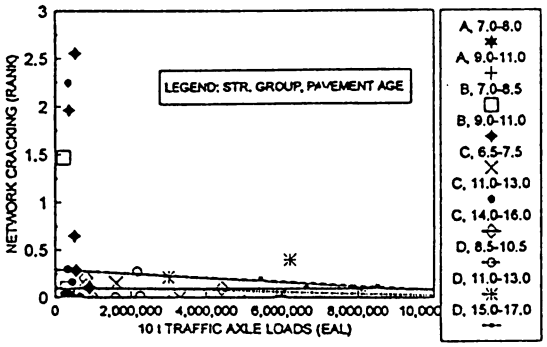


Fig. 13(a) Network Cracking Rank vs Traffic Loading

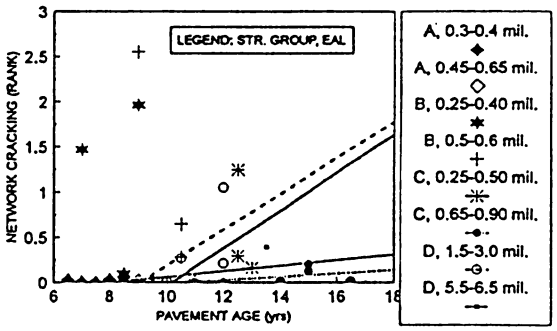


Fig. 13(b) Network Cracking Rank vs Pavement age

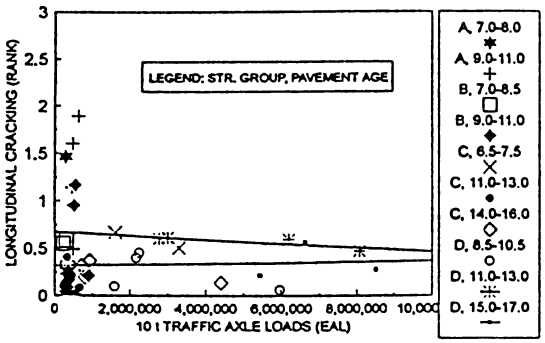


Fig. 14(a) Longitudinal Cracking Rank vs Traffic Loading

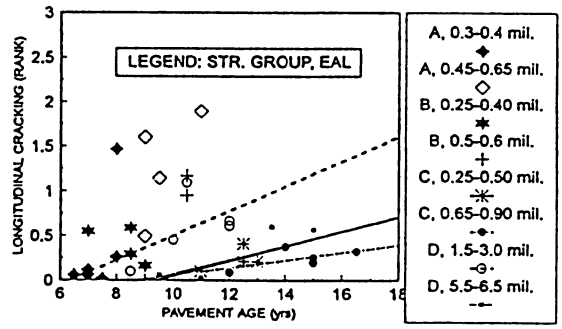


Fig. 14(b) Longitudinal Cracking Rank vs Pavement age

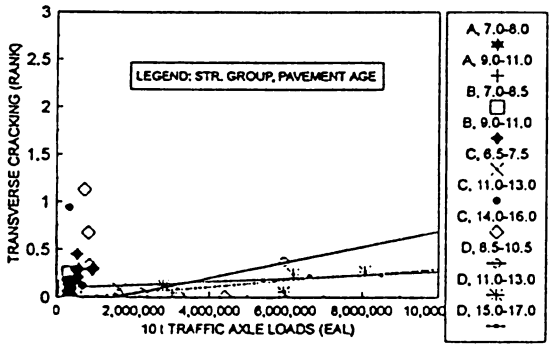


Fig. 15(a) Transverse Cracking Rank vs Traffic Loading

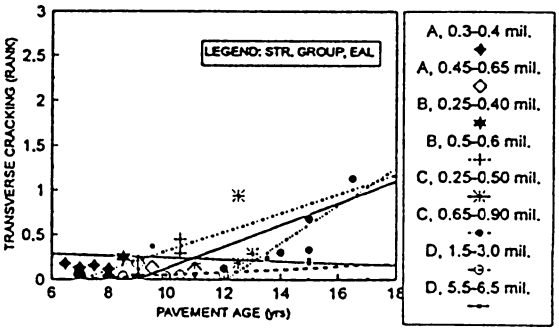


Fig. 15(b) Transverse Cracking Rank vs Pavement age

'aging' usually takes the form of irregular or 'map' cracking. Vallerga (1981) found that as the binder becomes embrittled with age, load associated block cracking develops in wheel tracks, and develops into cracks of all patterns whatever the initial cause of cracking. Furthermore, Paterson and Chesher (1986) found that this hardening over time consequently reduces the fatigue life of the surfacing material. Since all the pavements had same AC texture, these experiences confirm results in Figs. 13 i.e. the cyclic effect of pure environmental forces (temperature, ageing, moisture) are the main factors in all patterns of network cracking, alligator, block, or map. Traffic loading may determine the onset of fatigue cracking but is of secondary importance thereafter and in other forms of network cracking.

Longitudinal Cracking. Fig. 14(a) shows no trendy relationship between longitudinal cracking and traffic loading while Fig. 14(b) shows a strong relationship where longitudinal cracking increase with pavement age. Although longitudinal cracks are said to be caused by construction defects, these results show that environmental forces have a strong influence. Shrinkage cracking may initially appear in the form of longitudinal cracks along construction joints (weakest points) before spreading into right-angled patterns (O'Flaherty 1988). Day (1995) reported that water seepage through the joints of concrete curbs may cause cracks parallel to the curbs and gutters due to heave of the compacted clay subgrade. These studies and practical experiences support the findings.

Transverse Cracking. Fig. 15(a) shows that transverse cracking slightly increase with EAL i.e. there is a little influence due to traffic loading. Although most transverse cracking are documented to be related to low-temperature cracking, these results show that difference in traffic loading alone can increase or initiate transverse cracking. Since this research cannot explain mechanisms by itself, further physical research is called for. Fig. 15(b) shows the environmental influence on transverse cracking. Environmental forces causing transverse cracking are known to be due to the cyclic effect of temperature variation and hardening of the asphalt (Haas et al. 1994).

CONCLUSIONS

This research provides a methodology for separating and analyzing traffic loading and environmental effects on pavement deterioration using a large amount of historical data. These effects, as portrayed here, are different from those usually referred to in other relationships by the fact that they are pure. For example, the effect of traffic loading is completely without the cyclic effect of environmental forces.

Although the relationships observed here were obtained statistically and no mechanistic or cause-and-effect relationship between work load and 'assessed' distress is guaranteed, the number of data used and the same trends shown by pavements with same characteristics from different places make the results trustworthy.

The following conclusions can be drawn:

Rutting. (1) On the overall, traffic loading is the main force behind pavement rutting. There is more increase in rutting due to traffic loading than due to mere environmental forces. Traffic loading influences pavement rutting in a power function form i.e. more rutting occurs in early stages of loading than later on. Subgrade strength (CBR) is, in the long run, instrumental in reducing pavement rutting due to traffic loading.

(2) Environmental effects on pavement rutting increases exponentially i.e. they become severer with time. Both subgrade CBR and T_A influence environmental effects on pavement rutting but in different ways. While the difference in effects on pavements with different CBR values is more evident with time, the difference in effects due to different T_A values is evident from the beginning and is maintained throughout. Thus CBR determines how severe environmental effects are going to be with time while T_A acts as a uniform force against environmental effects on pavement rutting.

(3) The initial pavement rut depth depends on pavement layers thicknesses, materials, and construction quality. This, together with conlusion 2 above, shows that the pavement strength highly determines pavement rutting in the early stages of pavement life.

Cracking. (1) Results on network cracking show no defined relationship between it and axle load repetitions. Since network cracking consists mostly of alligator cracking, it is concluded that traffic loading determines the onset of fatigue cracking but does not have a defined relationship thereafter. Network cracking increases with environmental forces depicted by age. The cyclic effect of environmental forces due to changes in temperature, ageing, and moisture have a

direct effect on network cracking i.e. alligator, block or map cracking

(2) Longitudinal cracking is influenced by environmental forces and increases with its cyclic effect.

(3) Results show that transverse cracking increases with environmental forces i.e. due to cyclic temperature changes, and also that traffic loading has an effect of increasing transverse cracking.

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